ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSISTANT EDITORS

H. E. MCKINSTRY, *Harvard University*
M. LEROY JENSEN, *Yale University*
JOE W. PEOPLES, *Wesleyan University*
J. D. BATEMAN, *Toronto, Ont.*
R. H. JAHNS, *California Institute of Technology, Pasadena*

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
Madison, Wisconsin

D. F. HEWETT
U. S. Geological Survey, Pasadena, Calif.

A. I. LEVORSEN
Tulsa, Okla.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
U. S. Geological Survey, Washington, D. C.

A. N. SAYRE
U. S. Geological Survey, Washington, D. C.

L. C. GRATON
Harvard University, Cambridge, Mass.

E. S. MOORE
Univ. of Toronto, Toronto, Can.

PER GEIJER
Djursholm, Sweden

P. F. FOURMARIER
Liège University, Liège, Belgium

M. S. KRISHNAN
Geological Survey, Calcutta, India

T. W. GEVERS
University of the Witwatersrand, Johannesburg, S. Africa

C. F. DAVIDSON
Geological Survey, London, England

J. A. BROGGI
Instituto Geologica, Lima, Peru

TAKEO WATANABE
University of Tokyo, Tokyo, Japan

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1954

HUGH E. MCKINSTRY, *President*
THERON WASSON, *Vice-President*
OLAF N. ROVE.....*Secretary*
U. S. Geological Survey, Washington 25, D. C.
JOSEPH T. SINGEWALD, JR...*Treasurer*
Johns Hopkins Univ., Baltimore, Md.

Councilors

1954	*1955*	*1956*
CLAYTON G. BALL	JOSEPH L. GILLSON	RICHARD M. FOOSE
MURL M. GIDEL	JAMES A. NOBLE	W. R. LANDWEHR
ROGER H. MCCONNEL	EDWARD SAMPSON	HUGH M. ROBERTS

Regional Vice-Presidents

PAUL RAMDOHR, Europe.....C. O. SWANSON, North America
TAKAO SAKAMOTO, Asia.....VICTOR E. OPPENHEIM, South America
J. AUSTEN BANCROFT, Africa.....HAROLD G. RAGGATT, Australia

Executive Committee

HUGH E. MCKINSTRY, *Chairman* JOSEPH T. SINGEWALD, JR. THERON WASSON
DONALD M. DAVIDSON OLAF N. ROVE

Finance Committee

JOSEPH T. SINGEWALD, JR., *Chairman* ROBERT P. KOENIG
DONALD M. DAVIDSON OLAF N. ROVE, *Ex-officio*

Program Committee

ARTHUR L. HOWLAND, *Chairman* JAMES A. NOBLE WALTER S. WHITE
RICHARD H. JAHNS OLAF N. ROVE, *Ex-officio*

Committee on Publications

JOHN S. STEVENSON, *Chairman* DONALD E. WHITE OLAF P. JENKINS

Nominating Committee

JOSEPH L. GILLSON, *Chairman* JOHN K. GUSTAFSON IRA H. CRAM

Admissions Committee

ROGER MCCONNEL, *Chairman* DAVID L. EVANS C. PHILLIP JENNEY
W. R. LANDWEHR GEORGE B. LANGFORD

Auditing Committee

FRANCIS G. WELLS, *Chairman* A. NELSON SAYRE

Coal Research Committee

Executive Members: Elso S. Barghoorn, *Chairman,* Paul Averitt,
Clayton G. Ball, G. H. Cady

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 49 NOVEMBER, 1954 No. 7

THE WHITE PINE COPPER DEPOSIT, ONTONAGON COUNTY, MICHIGAN[1]

WALTER S. WHITE AND JAMES C. WRIGHT

CONTENTS

PAGE

Abstract 676
Introduction 676
The Nonesuch shale 680
The cupriferous zone 680
Lower sandstone 681
Parting shale 682
Upper sandstone 683
Upper shale 683
Rocks above the cupriferous zone 684
Paleogeography of rocks of the cupriferous zone 685
Sandstones 685
Thinly laminated beds just above sandstones 687
Massive siltstone 687
Summary 688
Persistence of units away from White Pine 688
Structure 690
Faults 691
Folds 691
Structure near White Pine 691
Geology of copper minerals and related minerals 695
Relative abundance of minerals 695
Stratigraphy of copper distribution 696
Laminated bed, base of parting shale 702
Massive bed, middle parting shale 703
Laminated bed, base of upper shale 704
Copper in and above massive bed, upper shale 705
Copper in sandstone 706
Relation of copper to fissures and faults 708
Copper in fissures and joints 708
Relation of copper in shale to faults and fissures 709
Origin of copper 712
Copper in the Nonesuch shale in other areas 715
References 716

[1] Publication authorized by the Director, U. S. Geological Survey.

ABSTRACT

Copper, largely in the mineral chalcocite, is found in the lowermost beds of the Nonesuch shale over many square miles near White Pine, Ontonagon County, Mich. The Nonesuch shale, of late Keweenawan age, is about 600 feet thick and is composed largely of gray siltstone. It overlies 2,300 to 5,500 feet of red sandstones and conglomerates, the Copper Harbor conglomerate. This formation, in turn, overlies the middle Keweenawan Portage Lake lava series, in which occur the famous native-copper deposits of the south shore of Lake Superior. The White Pine mine is 45 to 70 miles west-southwest of the principal native copper mines.

The copper-bearing beds at White Pine are primarily in the lower 20 to 25 feet of the Nonesuch shale. This cupriferous zone is divided in local usage into four stratigraphic units, which are, in ascending order, the lower sandstone (the uppermost bed of the Copper Harbor conglomerate), the parting shale, the upper sandstone, and the upper shale. The sequence of beds is almost identical in the upper and parting shales, suggesting cyclic sedimentation. This sequence and the distribution of sedimentary facies are attributed to two submergences, separated by an emergence, of a deltaic area.

Practically all the copper occurs in the upper and parting shales, except in a small area near the White Pine fault where it is abundant in the upper and lower sandstones. It is present in five different layers in amounts that average from 1 to 3 percent. The total amount of copper in each bed is generally higher where the bed is thick, and thickness, in turn, seems to be greatest in areas that were hollows away from the main channel or channels of the ancient delta. Copper content of the shale beds typically decreases as their sand content increases. The extent of individual copper-bearing beds 1 to 3 feet thick is measurable in square miles.

The local occurrence of copper in the upper and lower sandstone beds can be reasonably explained as the result of hydrothermal transportation from the White Pine fault up the dip of the relatively permeable sandstone to the crest of an adjacent anticline. Distribution of copper in the parting and upper shales, on the other hand, seems to be completely independent of local structure, faults, and rock permeability. For the area as a whole the control is lithologic and stratigraphic. Probably the copper was dropped into or precipitated within the original mud; it may conceivably have replaced with exquisite detail something else that was so deposited.

INTRODUCTION

THE copper deposit at White Pine, Ontonagon County, Mich. (Fig. 1), is separated both geographically and stratigraphically from the famous native-copper deposits of the south shore of Lake Superior. The principal native-copper deposits lie 45 to 70 miles east-northeast of White Pine. Stratigraphically these native-copper deposits occur in the middle Keweenawan Portage Lake lava series (13),[2] whereas the deposit at White Pine lies at the base of the upper Keweenawan Nonesuch shale; the Copper Harbor conglomerate, 2,300 to 5,500 feet thick, separates the two formations.

The lowermost beds of the Nonesuch shale seem to be most cupriferous in the vicinity of the Porcupine Mountains (Fig. 1). Two mines, the Nonesuch ("H" in Fig. 1) and White Pine (1 mile northwest of "I," Fig. 1), intermittently exploited patches of high-grade ore from 1870 to 1920, and the formation

[2] Numbers in parentheses refer to References at end of paper.

was explored by drilling, test-pitting, or underground exploration at a number of other places. The Copper Range Co., through its subsidiary the White Pine Copper Co., is now undertaking to mine a multimillion-ton body of low-grade ore underlying an area of several square miles (parts of shaded area, Fig. 1) north and east of the old White Pine mine (2, 10).

The underground workings and diamond drill holes by which this large ore body has been developed provide a wealth of information on the geology of copper minerals in the Nonesuch shale. Several characteristics of the copper distribution indicate that the metal was deposited before deformation and probably before lithification of the rocks in which it now occurs. Locally there has been hydrothermal enrichment of sandstone beds, forming ore deposits like that at the old White Pine mine. This paper presents a preliminary geologic description of the cupriferous zone at the base of the Nonesuch shale and the distribution of copper minerals within it and gives the reasons for the conclusion that the copper deposit was present before lithification and deformation. This is part of a more detailed study of the Nonesuch shale that the authors are preparing.

The Nonesuch shale and its copper have been briefly described by Whittlesey (15), Rominger (11, 12), Irving (5), and Butler, Burbank, and others (3). Nishio (9) investigated the relation of carbonaceous matter to the native copper in the sandstone of the old White Pine mine. The most complete description of the occurrence of copper, largely the work of Dr. T. M. Broderick, is contained in U. S. Geological Survey Professional Paper 144 (3, p. 169–175). This study was based almost entirely on observations in the old White Pine mine. As will be apparent from the descriptions that follow, the character and distribution of copper in the old White Pine mine is closely related to structure and permeability and is very different from that in the low-grade deposit now being exploited. These differences in mode of occurrence are here attributed to differences in the geologic history of the copper.

The geologic data presented here have been collected intermittently over a period of six years as part of a geologic study of the Michigan Copper District by the U. S. Geological Survey. The senior author made a detailed study of the mile-long exploratory drift at the Schacht shaft ("I," Fig. 1) as it was being driven in 1946–47, with primary emphasis on a study of the faults and geologic structure. During the years 1949–52 the authors examined all the core preserved from the Copper Range Co. drilling and studied all the exposed sections and outcrops of the Nonesuch shale that they could find in the 125 miles between Calumet, Mich., and the Bad River north of Mellen, Wis. (Fig. 1).

This study could not have been undertaken without the whole-hearted cooperation of officials of the Copper Range Co. and the White Pine Copper Co. The authors are particularly grateful to Morris F. LaCroix, President, and Harold B. Ewoldt, Vice-president, to W. E. Romig, formerly General Manager, and to John R. Rand, Geologist, for unrestricted access to mine workings, drill core, and assay and other engineering records, and for many friendly courtesies throughout the work. They are also much indebted to Dr. T. M.

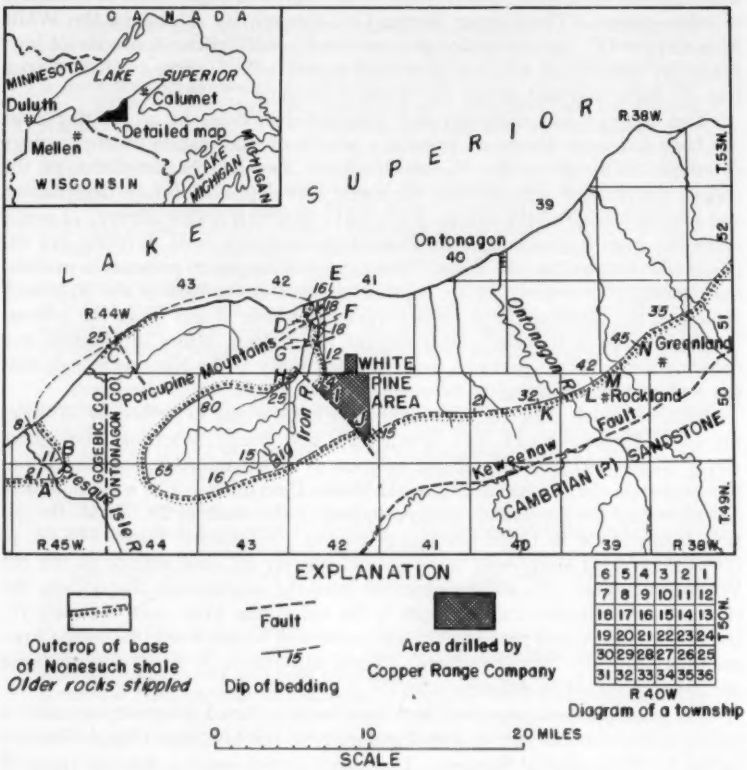


FIG. 1. Index map showing location of White Pine area and location and attitude of the base of the Nonesuch shale. Localities referred to in text and on Figure 6 indicated by letters as follows: A. Presque Isle River, SW¼ sec. 4, T. 49 N., R. 45 W.; B. Tiebel Creek, north of the east quarter corner, sec. 33, T. 50 N., R. 45 W.; C. One mile southwest of Lone Rock, NW¼ sec. 26, T. 51 N., R. 44 W.; D. Little Iron River, Scranton silver mine, SW¼ sec. 13, T. 51 N., R. 42 W.; E. Big Iron River, below Greenwood camp, NE¼ sec. 13, T. 51 N., R. 42 W.; F. Big Iron River, Superior silver mine, SE¼ sec. 13, T. 51 N., R. 42 W.; G, Big Iron River, Collins silver mine, NE¼ sec. 25, T. 51 N., R. 42 W.; H, Little Iron River, Nonesuch mine, SE¼ sec. 1, T. 50 N., R. 43 W.; I. White Pine mine (Schacht shaft), see Fig. 7; J. White Pine drill hole 10–0, SE¼ sec. 24, T. 50 N., R. 42 W.; K. Gates Creek, NW¼ sec. 14, T. 50 N., R. 40 W.; L. Gravel pit near Rockland, SE¼ sec. 5, T. 50 N., R. 39 W.; M. Rockland Creek, near center of the W½ sec. 4, T. 50 N., R. 39 W.; N. McGuire Creek, Greenland, NW¼ sec. 28, T. 51 N., R. 38 W.

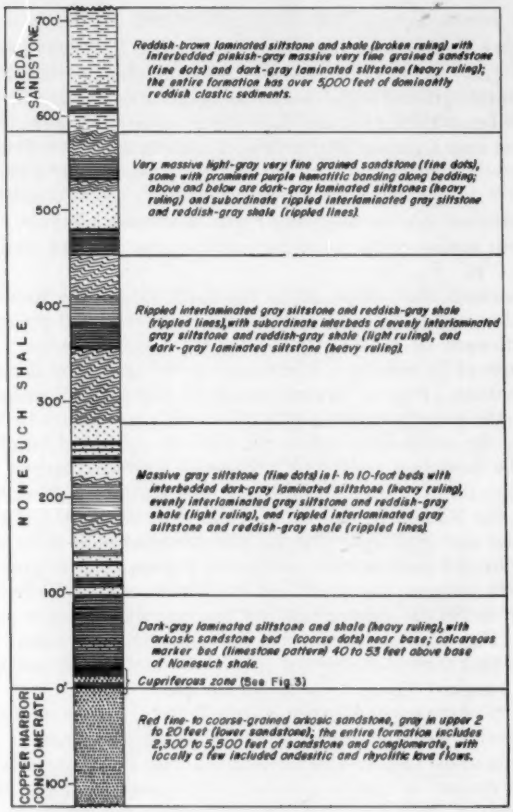

FREDA SANDSTONE
NONESUCH SHALE
COPPER HARBOR CONGLOMERATE
700'
600'
500'
400'
300'
200'
100'
0'
100'
Reddish-brown laminated siltstone and shale (broken ruling) with interbedded pinkish-gray massive very fine grained sandstone (fine dots) and dark-gray laminated siltstone (heavy ruling); the entire formation has over 5,000 feet of dominantly reddish clastic sediments.
Very massive light-gray very fine grained sandstone (fine dots), some with prominent purple hematitic banding along bedding; above and below are dark-gray laminated siltstones (heavy ruling) and subordinate rippled interlaminated gray siltstone and reddish-gray shale (rippled lines).
Rippled interlaminated gray siltstone and reddish-gray shale (rippled lines), with subordinate interbeds of evenly interlaminated gray siltstone and reddish-gray shale (light ruling), and dark-gray laminated siltstone (heavy ruling).
Massive gray siltstone (fine dots) in 1- to 10-foot beds with interbedded dark-gray laminated siltstone (heavy ruling), evenly interlaminated gray siltstone and reddish-gray shale (light ruling), and rippled interlaminated gray siltstone and reddish-gray shale (rippled lines).
Dark-gray laminated siltstone and shale (heavy ruling), with arkosic sandstone bed (coarse dots) near base; calcareous marker bed (limestone pattern) 40 to 53 feet above base of Nonesuch shale.
Cupriferous zone (See Fig 3)
Red fine- to coarse-grained arkosic sandstone, gray in upper 2 to 20 feet (lower sandstone); the entire formation includes 2,300 to 5,500 feet of sandstone and conglomerate, with locally a few included andesitic and rhyolitic lava flows.

FIG. 2. Columnar section of Nonesuch shale. Section measured on Big Iron River 0.5 to 1 mile from mouth, in sec. 13, T. 51 N., R. 42 W. (locality E, Fig. 1). Bottom 20 feet of Nonesuch shale is from little Iron River (locality D, Fig. 1), and Freda sandstone is from drill hole near lake shore 0.3 mile east of mouth of Big Iron River.

Broderick, Chief Geologist of Calumet & Hecla, Inc., for much valuable information on the old White Pine mine.

Members of the Geological Survey who have provided material assistance in the work and who have contributed much by discussion of the problems involved include H. R. Cornwall, R. W. Swanson, and E. S. Davidson. Finally, the authors are most indebted to Ralph S. Cannon, Jr., of the Geological Survey, who, before the study began, suggested the possible sedimentary origin of the copper, and whose interest in the study has been a constant stimulation.

THE NONESUCH SHALE

The upper Keweenawan Nonesuch shale (5, p. 220–224) is a sequence of dominantly gray, well-bedded siltstone and shale that is distinct from the red to brown coarser grained rocks of the formations above and below. The thickness ranges from 250 feet at the Bad River north of Mellen, Wis., to more than 700 feet near Calumet, Mich. (Fig. 1), but is close to 600 feet over most of the intervening distance. The formation is separated by a sharp boundary from the underlying Copper Harbor conglomerate (7, p. 680, 690) and is more or less transitional into the overlying Freda sandstone. Figure 2 is a generalized columnar section of the formation from a point near the mouth of the Big Iron River ("E," Fig. 1).

The Nonesuch shale crops out on the north side of the Keweenawan trap range, which is upheld by the Portage Lake lava series and generally dips 15° to 45° northward or northwestward toward Lake Superior. The slightly sinuous course of its outcrop is interrupted by the structural dome of the Porcupine Mountains (Fig. 1), around which the outcrop belt makes an almost-closed loop; the beds dip rather gently (4° to 25°) away from Porcupine dome, except along the south flank, where the dips are steep and locally even overturned. The formation apparently disappears westward largely by a change of sedimentary facies. On the Bad River, just north of Mellen, Wis. (Fig. 1, inset map), the Nonesuch shale is represented by about 80 feet of gray laminated siltstone and shale beds that are interstratified with twice as much reddish sandstone and shale to form a 250-foot sequence; these gray rocks probably represent tongues that pinch out completely a little farther west. The northeastern end of the outcrop belt is at the lake shore 7 miles north of Calumet, Mich. (Fig. 1, inset map). The formation there is coarse grained and somewhat redder than in the central part of the outcrop belt and may likewise represent a marginal facies of the Nonesuch shale.

A majority of the upper Keweenawan sedimentary rocks on the south shore of Lake Superior had a southern source as shown by numerous observations of foreset beds in the Copper Harbor conglomerate and Nonesuch shale. The considerable amount of quartz and mica with minor amounts of jasper and specular hematite throughout the Nonesuch shale indicates that the streams that supplied the clastic material of the formation had their headwaters in an area of pre-Keweenawan rocks, such as those now exposed 10 miles or more south of the present outcrop. The nature of the Nonesuch rocks themselves indicates that they were probably shallow-water sediments. At least during the initial stage of deposition of this formation, the shoreline must have fluctuated back and forth across the area of the present outcrop.

The Cupriferous Zone

In the vicinity of the White Pine mine, copper is largely restricted to a distinct series of beds, about 25 feet thick, in the lowermost part of the Nonesuch shale and the uppermost part of the Copper Harbor conglomerate. For convenience of reference this group of beds will here be called the "cupriferous zone." The cupriferous zone is subdivided in present usage at White Pine

into four units, which are, in ascending order, the lower sandstone, the parting shale, the upper sandstone, and the upper shale. Figure 3 is a detailed columnar section of the cupriferous zone; the thickness of each individual unit in this section is the average for that unit (not weighted for area represented) as measured in about 75 drill cores from the White Pine drilling. The following paragraphs describe these units in ascending order.

Lower Sandstone.—In the vicinity of White Pine the sandstone at the top of the Copper Harbor conglomerate is fine- to coarse-grained without many

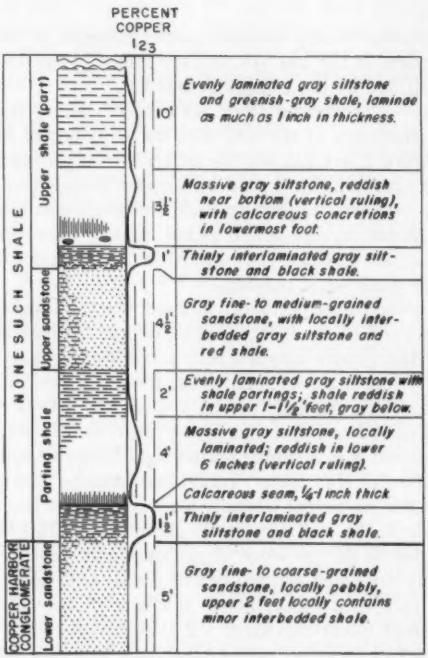

PERCENT COPPER
1 2 3
NONESUCH SHALE
Upper shale (part)
Upper sandstone
Parting shale
Lower sandstone
COPPER HARBOR CONGLOMERATE
10'
3½'
1'
4½'
2'
4'
1½'
5'
Evenly laminated gray siltstone and greenish-gray shale, laminae as much as 1 inch in thickness.
Massive gray siltstone, reddish near bottom (vertical ruling), with calcareous concretions in lowermost foot.
Thinly interlaminated gray siltstone and black shale.
Gray fine- to medium-grained sandstone, with locally interbedded gray siltstone and red shale.
Evenly laminated gray siltstone with shale partings; shale reddish in upper 1–1½ feet, gray below.
Massive gray siltstone, locally laminated; reddish in lower 6 inches (vertical ruling).
Calcareous seam, ¼-1 inch thick
Thinly interlaminated gray siltstone and black shale.
Gray fine- to coarse-grained sandstone, locally pebbly, upper 2 feet locally contains minor interbedded shale.

FIG. 3. Typical stratigraphic section of cupriferous zone, White Pine area, Michigan.

pebbles. The three principal granular constituents of the sandstone are fragments of mafic lava, quartz, and fragments of rhyolite, named in the most common order of decreasing abundance. The grains range from angular to subrounded. The interstices, generally 20 to 25 percent of the rock, are filled with calcite or, less commonly, with calcite and chlorite.

The uppermost 5 to 20 feet of the Copper Harbor conglomerate is generally grayish, in contrast with the prevailingly reddish or brownish color of the formation as a whole; this gray unit is called the lower sandstone, and Butler,

Burbank, et al. (3, p. 172) call it the "Second lode." Comparison of thin sections representing the grayish and reddish rocks suggests that the amount of hematite is only slightly different in the two and that the major difference is a higher ratio of chlorite to calcite in the matrix of the gray rock. The brick or chocolate color of many fine-grained sandstones of the Copper Harbor conglomerate, however, is probably due largely to interstitial earthy hematite.

In the old White Pine mine, both the lower and upper sandstones locally contain considerable carbonaceous matter in the matrix (3, p. 171; 9), but it is a negligible constituent of the sandstones over most of the area drilled by Copper Range Co.

The lower sandstone locally contains copper minerals in the uppermost 1 to 7 feet and was mined at the old White Pine mine. It is almost barren over most of the area drilled by the Copper Range Co.

Parting Shale.—The parting shale, despite its name, is dominantly siltstone. Both the thickness of the unit and the sequence of beds within it, as represented in Figure 3, are remarkably uniform over all but the southeastern quarter of the 10 square miles drilled by Copper Range Co. (Fig. 1).

The boundary between the parting shale and the lower sandstone is generally marked by a transition zone 3 to 6 inches thick. This transition rock consists of fine- to medium-grained gray sandstone with numerous irregular and discontinuous thin black-shale partings.

Above the transition zone is a bed 1 to 2 feet thick composed of thinly laminated gray siltstone and black shale; most individual laminae consist of a lower siltstone portion that grades upward into a black shale parting. Individual laminae are mostly less than 0.1 inch thick, though a few may be an inch or more; many of the shale partings are only films about 0.01 inch thick. The shale at the top of most laminae is sharply set off from the siltstone of the next succeeding lamina, and it is a simple matter to distinguish top from bottom in most hand specimens of this rock. Individual laminae pinch and swell, and some, at least, are not persistent laterally for more than a few feet. The ratio of siltstone to shale in the bed is typically about 2:1. The black color of the shale partings is due to the presence of carbonaceous matter.

Next above this laminated bed is a bed of massive siltstone 3 to 4 feet thick. A fraction of an inch to 2 inches above the base of this siltstone there is a remarkably persistent calcareous layer 0.2 to 1.0 inch thick. This layer has a very sharp contact at the base, cut by what look like tiny shale-filled shrinkage cracks, and a transitional upper boundary. The 6 inches of massive siltstone above this calcareous layer generally has a faintly reddish tinge, more conspicuous in artificial light than in sunlight. The bulk of the massive siltstone above this reddish zone is gray; it contains some scattered calcareous concretions and thin discontinuous calcareous layers just above the reddish zone. In the transition upwards from this massive bed, laminations become increasingly conspicuous. Contorted bedding and angular unconformities locally indicate some contemporaneous slumping during deposition.

The next higher subdivision is commonly composed of graded laminae ½ to 2 inches thick; dark-gray shale or mudstone at the top of each lamina grades down into gray siltstone below and has a sharp contact with the siltstone of

the next higher graded lamina. Individual laminae are persistent laterally for many tens of feet.

The next higher unit, the uppermost subdivision of the parting shale, is like the one immediately below except that the finer grained tops of individual laminae are conspicuously reddish. The coarser siltstone part of each pair may be gray, as in the unit below, or red.

The top of the parting shale locally has abundant mudcracks, and in some places this horizon is incised to depths of a foot or two by channels filled by the overlying upper sandstone.

The laminated bed at the base of the parting shale generally contains 1 to 5 percent copper as chalcocite and native metal, and the upper part of the massive siltstone bed typically contains 1 to 2 percent copper (Fig. 3).

Upper Sandstone.—The upper sandstone is very similar in appearance to the lower sandstone. It is generally a little finer grained, and pebbles are even less common than in the lower sandstone.

This bed shows more conspicuous change from place to place than do the other beds of the cupriferous zone, not only in thickness but also in lithology. In some places the upper sandstone is a single massive bed of more or less even-grained sandstone. In others it consists of several conspicuously graded beds a few inches to over a foot thick. Individual graded beds may contain material ranging in size from coarse pebbly sand to gray siltstone or red shale. Some graded beds contain nothing coarser than siltstone and are identical with layers in the uppermost parting shale beneath. The base of the upper sandstone is arbitrarily drawn at the base of the lowest sandstone layer.

The upper sandstone locally contains chalcocite or native copper, most commonly at or near the top. Like the lower sandstone, the bed is almost barren over most of the area drilled by the Copper Range Co.

Upper Shale.—The upper shale, in a broad sense, includes the next 20 to 40 feet of rock above the upper sandstone, but only the lower 7 or 8 feet is copper-bearing. The sequence of beds at the base of the upper shale is strikingly similar to the sequence in the parting shale (see Fig. 3). At the base is a unit almost identical lithologically with the thinly laminated gray siltstone and black shale at the base of the parting shale. It is generally less than a foot thick, and grades into the sandstone below through a transition zone lithologically like the one at the base of the parting shale. Above the laminated silt and shale is a massive bed 3 to 3.5 feet thick analogous to the bed in the middle of the parting shale. This massive bed is, furthermore, locally reddish in its lower part and gray above. Instead of a thin calcareous layer at its base, however, this massive bed contains one or two horizons with spheroidal calcareous concretions 1 to 3 inches in diameter in the reddish siltstone 6 to 12 inches above its base.

Above this massive bed the rock is gray siltstone with thin and very even dark-gray shale laminae. Individual laminae can be correlated on the basis of their thickness and spacing (like varves or tree rings) for distances of at least 1,000 feet. This evenly laminated unit is 5 to 15 feet thick over most of the drilled area. Where the unit is more than 6 or 8 feet thick the shale laminae in the upper part are commonly reddish. The top of the cupriferous

zone is generally less than 5 feet above the base of this evenly laminated unit.

The laminated bed at the base of the upper shale contains 1 to 5 percent copper as chalcocite or native metal, like its counterpart at the base of the parting shale. There is typically about 1 percent of copper in the upper part of the massive bed or just above, and locally the laminated rock 2 to 3 feet above the massive bed also contains 1 percent (Fig. 3).

Rocks Above the Cupriferous Zone

The lithology of the rocks above the cupriferous zone is briefly summarized in Figure 2. Most of the Nonesuch shale consists of well-bedded to laminated gray siltstones, more or less current rippled, with features like mudcracks and mud chips that suggest shallow-water deposition.

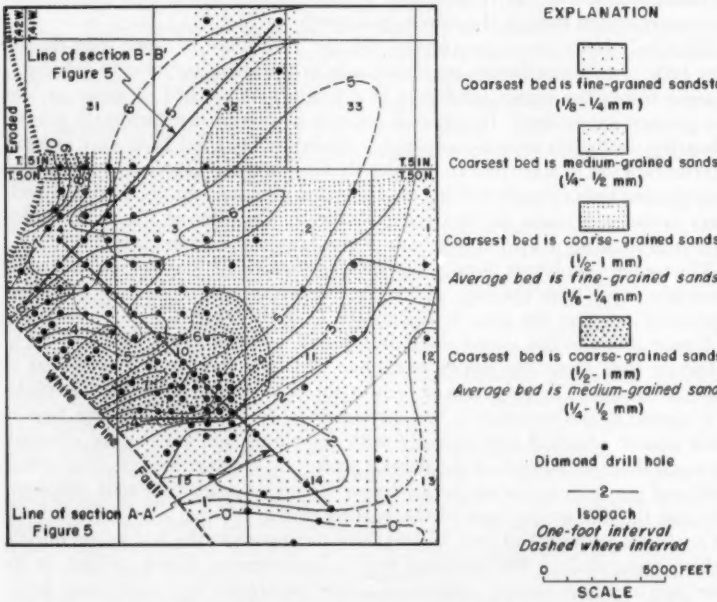

EXPLANATION
Coarsest bed is fine-grained sandstone (1/8 - 1/4 mm)
Coarsest bed is medium-grained sandstone (1/4 - 1/2 mm)
Coarsest bed is coarse-grained sandstone (1/2 - 1 mm)
Average bed is fine-grained sandstone (1/8 - 1/4 mm)
Coarsest bed is coarse-grained sandstone (1/2 - 1 mm)
Average bed is medium-grained sandstone (1/4 - 1/2 mm)
Diamond drill hole
—2—
Isopach
One-foot interval
Dashed where inferred
0 5000 FEET
SCALE
Line of section B-B' Figure 5
Line of section A-A' Figure 5
Eroded
White Pine Fault
T51N.
T50N.
R42W.

FIG. 4. Thickness and lithology of upper sandstone in cupriferous zone of the Nonesuch shale, White Pine area.

Within this series of beds one bed of unique lithology, called the marker bed, has outstanding value in regional stratigraphic correlation. It is about 10 feet thick, and its base lies 30 to 40 feet above the top of the upper sandstone. The rock of the marker bed is thinly interlaminated gray siltstone and dark-gray to black shale; it is studded with tiny white calcite blebs, both spherical and pancake-shaped, a millimeter or less in thickness. The marker bed

overlies a 3- to 4-foot bed of massive gray siltstone. This massive bed in turn overlies 1 to 2.5 feet of thinly interlaminated light-gray siltstone and dark shale, which has a distinctive striped appearance particularly in drill core. The base of this "striped" bed is taken as the top of the upper shale.

PALEOGEOGRAPHY OF ROCKS OF THE CUPRIFEROUS ZONE

The individual stratigraphic units described above are all present over a large area near the White Pine mine, and variations in their thickness and lithology furnish some evidence for the paleogeography of the area during deposition of the cupriferous zone. The sandstones are particularly useful in this respect.

The various changes of thickness and facies are illustrated in Figures 4 and 5. Figure 4 is a map showing the thickness and lithology of the upper sandstone, and Figure 5 contains two diagrammatic stratigraphic sections of the cupriferous zone, oriented at right-angles to one another, that cross the area of the White Pine copper deposit. The shorter section of Figure 5, B-B′, is 3 miles long, and the longer almost 5 miles; the vertical exaggeration is 400:1.

These sections (Fig. 5) are based wholly on diamond-drill information. The lithologic data for parts of section A-A′ are incomplete. For most holes, the core from the cupriferous zone was split, and the half not sent for assay is preserved for study. But all the core from the following holes in section A-A′ was used for assay, and therefore cannot be examined: X-6, X-8, X-11, X-13, X-19, 8-M, 9-N, 11-P. For these holes the writers have had to depend on the original drilling record, which generally distinguishes only sandstone, shale, and mixtures of the two. The only uncertain correlation lines on the diagram, however, are those that tie the four southeasterly drill holes to the rest of section A-A′.

The datum selected for the sections of Figure 5 is an average of the position of three surfaces, namely the base of the striped bed, the top of the laminated bed at the base of the upper shale, and the top of the laminated bed at the base of the parting shale. To determine the depth of the average surface in any hole, the depths of the three surfaces were simply added together and divided by three. This average surface, if drawn on Figure 5, would be represented by a horizontal line 29 feet above the base lines of section A-A′ and B-B′; all other bedding planes are drawn at their appropriate distances up or down from this average plane. If one actual surface had been used as a datum, instead of the average plane, all its own irregularities would be carried over to maps or diagrams of other surfaces that were measured up or down from it, but using an average surface reduces the magnitude of such irregularities.

Sandstones

Figure 4 shows the thickness and lithology of the upper sandstone in most of the area drilled by the Copper Range Co. This bed is thick and coarse along a line that trends northeast across the midpoint of sec. 10, T. 50 N., R. 42 W. Where this line crosses the southeast drift from the Schacht shaft

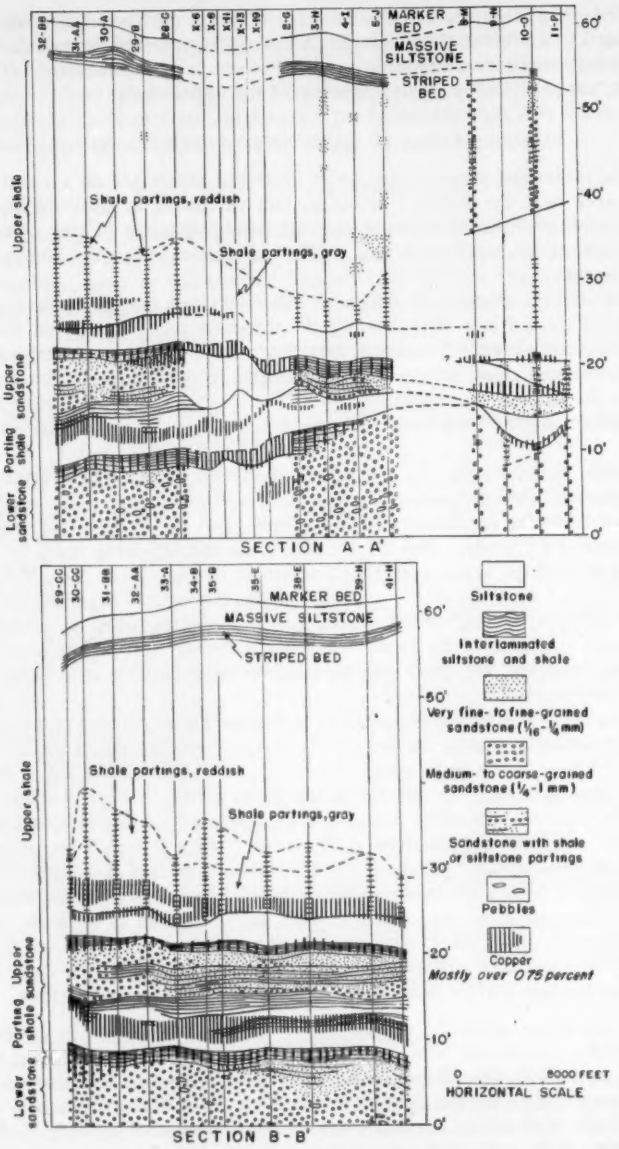


FIG. 5. Stratigraphic cross sections of White Pine area. For location of sections see Fig. 7.

(SW¼ sec. 10), channels as much as 2 feet deep trending N. 50°–60° E. cut the upper part of the parting shale. The upper sandstone thins and becomes finer grained northeastward along this channel (Fig. 4) and also southeastward away from the channel. Both the tonguelike form of this body of sandstone and the presence of mudcracks and channels at its base suggest that the body is deltaic, deposited in shallow water, or perhaps even in part subaerial. The upper sandstone becomes still thicker to the northwest, and thus suggests that the channel through sec. 10 may be only one distributary in a system of channels feeding a large delta; another channel seems to lie just west of the drilled area.

The topography of the top of the lower sandstone probably had some such form as is shown by its profile in Figure 5. This form is not greatly changed if any of several individual beds are assumed to be horizontal. The outstanding feature of this surface is the large prominence near the eastern end of section A-A′ (Fig. 5, drill holes 5-J and 8-M). There is not enough information to define the top and eastern side of this prominence, but it is interpreted as a constructional form built up along a channel in a sandstone delta analogous to the body of upper sandstone. The highest points of this deposit would be the levees containing the channel itself. The stratigraphy of drill hole 10-O suggests that the prominence separates two low-lying areas.

Thinly Laminated Beds Just Above Sandstones

The thickness and character of thinly interlaminated gray siltstone and black shale at the base of the parting and upper shales are systematically related to the tops of the sandstone beds that underlie them. In general, the siltstone-and-shale facies is thickest and most free from sandstone laminae in relatively low places near but down the slope from the relatively high places here interpreted as ancient deltaic tongues.

The laminated bed at the base of the parting shale is 1.5 to 2.5 feet thick and sand-free in drill holes 29-B, 28-C, and probably in holes X-6 to X-19 (section A-A′, Fig. 2); these characteristics prevail for a mile northeast of the section, beyond which point the bed becomes sandier though not thinner. The bed is thinner and sandy to the northwest and thicker and sandy to the southeast.

The laminated bed at the base of the upper shale is thickest and relatively free from sand laminae in holes 2-G to 5-J (section A-A′, Fig. 5), southeast of the prominent tongue of upper sandstone in section 10, T. 50 N., R. 42 W. (Fig. 4); the axis of this sandstone tongue goes through drill hole X-6 in section A-A′, Figure 5. In general the laminated bed at the base of the upper shale is thin where the upper sandstone is thick, and thick where the sandstone is thin throughout the area. It thickens from 6 inches or less in the northwestern part of the area of Figure 4, where it is relatively sandy, to 2 feet in the southeast corner.

Massive Siltstone

The massive siltstone beds in both parting shale and upper shale also thicken gradually away from elevations. The massive bed in the parting

shale thickens westward, away from the prominence at the top of the lower sandstone. The massive bed near the base of the upper shale thickens eastward away from the thickest and coarsest part of the upper sandstone. Evidently there was a tendency for these siltstone beds to fill in depressions and subdue the relief that existed before their deposition. This result was brought about in part, at least, by slumping; contorted bedding has been observed underground in the lower of the two beds.

These massive siltstone beds represent an abrupt change of some sort from the conditions that prevailed during deposition of the underlying thinly laminated beds. Deepening of the water is suggested as a cause. Inundation of the levees or bars protecting the stagnant depressions would make the water more open and expose the bottom to more active agitation by waves. The reddish color of the lower part of both massive beds suggests that the waters were at first well aerated and oxidizing as a result of this agitation. The gray color and preservation of some laminae in the upper part of the beds, on the other hand, indicate a tendency to revert to quieter, more stagnant conditions with the passage of time; these conditions could have been brought about by still further deepening, or by rebuilding of the levees or bars protecting the depressions.

Summary

In summary, there is here a repeated sequence of beds, (1) sandstone, (2) thinly interlaminated shale and siltstone, (3) massive gray siltstone, reddish near base, and (4) evenly laminated siltstone, with gray shale partings below and red above; the repetition of this sequence represents cyclic sedimentation. The sequence of changes up to and including the massive gray siltstone can be explained as the consequence of progressive inundation of a sand plain, with deltas of sand built out beyond the main shoreline at the mouths of streams. The extent to which these deltas were subaerial is not known, but the silts and shales of the parting and upper shales are believed to have been deposited in the lagoons, ponds, or swamps between separate distributaries.

The upper sandstone, which initiates the second cycle, was probably deposited in shallower water than the massive siltstone below it, as mudcracks are locally abundant at its base. But whether the shallowing was the result of sedimentation or of a relative lowering of water level is not readily determined. There was evidently some shifting of watercourses between the first and second cycles; the lower sandstone was built up highest in the southeastern part of the area, whereas the thickest and coarsest deposit of the upper sandstone is in the northwestern part.

PERSISTENCE OF UNITS AWAY FROM WHITE PINE

Each of the main stratigraphic units found in the vicinity of White Pine has been found at other localities up to 20 miles from White Pine, east, north, and west of the Porcupine Mountains (Fig. 1). Figure 6 shows diagrammatically the units recognized at various localities in which all or part of the cupriferous zone or the overlying marker bed is exposed. The letter symbols identifying

individual stratigraphic sections are also shown on Figure 1, the index map.

The lower parts of the sections near Lone Rock (C) and on the Presque Isle River (A) cannot be reliably correlated with those east of the Porcupine Mountains (D-J). Correlations between individual sections east of the mountains, however, are relatively reliable. As shown by Figure 6, the major subdivisions of the cupriferous zone (upper and lower sandstones, upper and parting shales) can be identified at most places where exposures are adequate

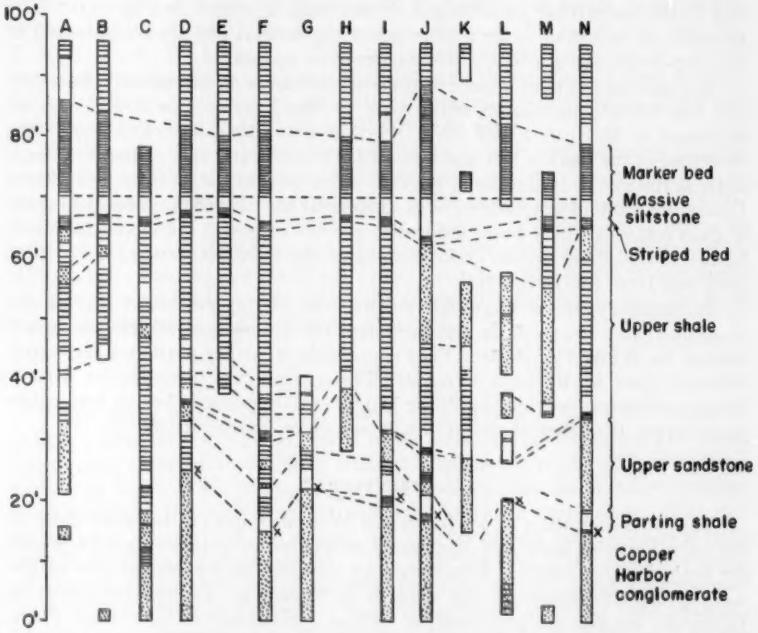


FIG. 6. Columnar sections of the lower part of the Nonesuch shale. Localities are shown on the map, Fig. 1. Patterns are as follows: stippling, sandstone; blank, massive siltstone; widely spaced lines, laminated siltstone; closely spaced lines, thinly interlaminated siltstone and shale. The presence of the calcareous layer at the base of the massive bed in the parting shale is indicated by "x." Black to red shale is also abundant 15 to 39 feet below the lowest shale shown on section C (near Lone Rock).

for 23 miles east from Nonesuch mine (H, Fig. 1) to McGuire Creek (N), and for at least 5 miles north (D) and 4 miles southeast (J) of White Pine (I). The same subdivisions were also recognized (1, p. 58–60) in drilling and underground development in the vicinity of the White Pine Extension mine (sec. 7, T. 50 N., R. 43 W.), 8 miles west of White Pine.

The thin calcareous seam at the base of the massive bed in the parting

shale (indicated in Fig. 6 by "X" in sections where it was found) was identified in practically all sections where the base of the Nonesuch shale is exposed. A calcareous layer of the same character was common in fragments on the dump (now mostly removed for use as road metal) of the White Pine Extension mine (8 miles west of White Pine), which had two long development drifts on the parting shale. This thin layer, therefore, seems to be more or less persistent for a minimum distance, from east to west, of 28 miles.

In the rocks above the cupriferous zone, the persistence of the marker bed and of the underlying massive and striped beds is shown in Figure 6. The presence of sandstone at or a little below the striped bed should be noted in the two westernmost and the five easternmost sections.

Beyond the limits of Figure 1, present exposures do not afford a basis for any bed-for-bed correlation either west of the Presque Isle River (A) or northeast of McGuire Creek (N). A thin bed with a few calcareous blebs like those of the marker bed was found 75 feet above the base of the Nonesuch shale at the mouth of the Black River, 5 miles west of the Presque Isle River. Sandstone is found interbedded with siltstone at the base of the Nonesuch shale at most other localities where exposures are fair or good. It should be noted, however, that there are no good sections of the basal Nonesuch for 36 miles northeast from McGuire Creek.

In summary, the stratigraphic subdivisions of the lowermost part of the Nonesuch shale are more or less persistent for distances of 20 miles east and west of the White Pine mine. They may continue farther northeast, but exposures are poor for the next 36 miles. The environment favorable for deposition of sediments like those at White Pine therefore existed over an area many times larger than that of the White Pine copper deposit itself.

STRUCTURE

The Nonesuch shale of Michigan and Wisconsin lies on the south flank of the Lake Superior basin and dips gently northward or northwestward towards the basin at most places. Representative attitudes in the central part of the outcrop belt are shown by dip symbols in Figure 1. Farther southwest in Wisconsin the dips are very steep to vertical. Northeast of Greenland, Mich. (Fig. 1), dips range from 40° to 55° NW. for the first 30 miles and are mostly 20° to 30° NW. still farther to the northeast.

The south flank of the Lake Superior basin is interrupted by the uplift now marked by the Porcupine Mountains (Fig. 1). The Nonesuch shale dips, in general, away from the uplift, though locally it is disrupted by faults as on the east flank of the uplift or overturned as along the south side. Between this uplift and the main Keweenawan trap range to the south are two synclinal areas underlain by the Nonesuch shale and the younger Freda sandstone. The syncline south and southeast of White Pine and Nonesuch (I and H in Fig. 1) will be referred to here as the Iron River syncline, and the other, crossed by the lower course of the Presque Isle River, will be called the Presque Isle syncline. The base of the Nonesuch shale probably attains depths of 3,000 to 5,000 feet below the surface in the Iron River syncline. Along the line of the

Presque Isle River the base of the Nonesuch is probably nowhere more than 1,200 to 1,300 feet below the surface, though the depth must increase to the northwest along the axis of the syncline.

Faults

The Nonesuch shale is much broken in places by faults. Some fairly large faults, with offsets ranging from a quarter of a mile to a mile, are shown in Figure 1. One of these, the White Pine fault described below, is the major tectonic feature of the White Pine area; it trends northwest almost bisecting T. 50 N., R. 42 W. (Fig. 1). Two faults trending east-northeast are shown offsetting the base of the Nonesuch shale between White Pine (I) and the lake shore. Another, marked by a brecciated zone almost 500 feet wide at the lake shore, is shown near Lone Rock at locality C in Figure 1.

Minor faults, too small to show on Figure 1, with displacements ranging from a foot or less to many tens of feet, are seen in stream beds where exposures are good. Most of the small minor faults have a little gouge or breccia. Secondary minerals, principally calcite, are abundant in some; quartz, and even traces of copper or chalcocite are also found. Faults with dips of less than 60° are not common, and many are nearly vertical. The larger minor faults are generally marked by a break in the continuity of outcrop, and the fault planes themselves cannot be directly observed.

Folds

Folds range in size from less than a foot to 6 or 7 miles from crest to trough. Most of the folds observed in the field and underground are bends due to drag along faults. Faults without drag are more common than those with drag, but it is not unusual to see the bedding bent up or down, or even more complexly crumpled, within a foot or two of a small fault. The disturbed zone may extend for several feet out on one or both sides of a fault with 20 or 30 feet of displacement. The beds exposed in the Big Iron River are much crumpled for several hundred feet near the two large faults shown north of White Pine in Figure 1. Even the anticline at White Pine (Fig. 7) is most simply interpreted as the result of dragging down of the beds on the northeast side of the White Pine fault.

In the curved parts of folds the rocks—whether shale, siltstone, sandstone, or conglomerate—are normally much fractured. They are cut by many tiny faults that lack notable continuity. Bending without breaking—continuous deformation—is the exception, even in the most shaly beds.

Structure Near White Pine

White Pine Fault.—The structure of the Nonesuch shale in the vicinity of White Pine is dominated by the White Pine fault (Fig. 7). This fault strikes northwest and dips steeply northeast at the old White Pine mine (3, p. 172). Its trace to the southeast, as shown in Figure 7, is based on the reasonable assumption that it underlies a mile-wide gap in the hills to the southeast of

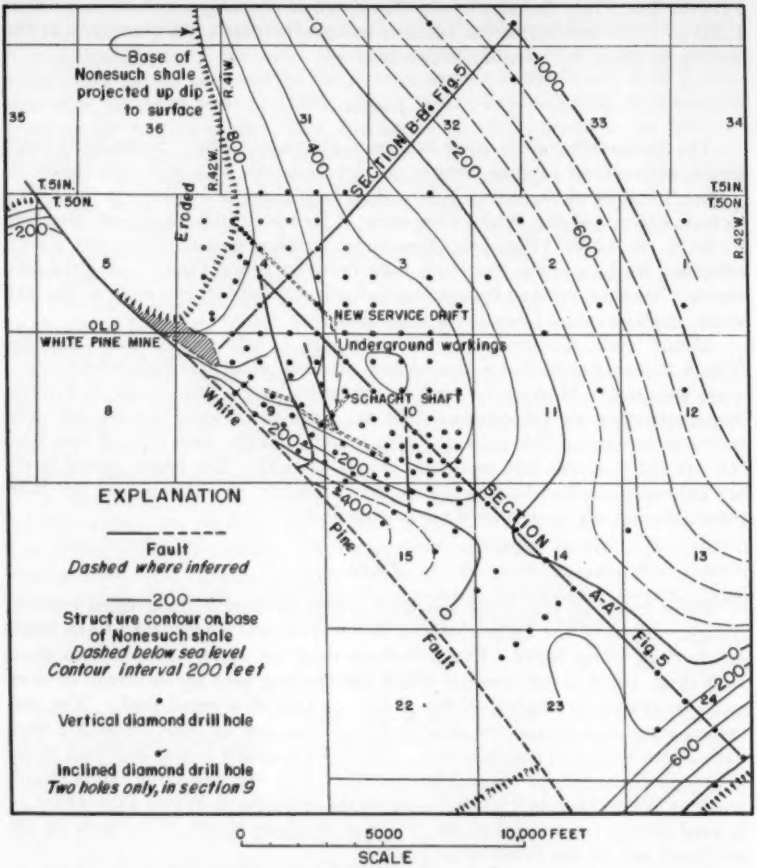


FIG. 7. Structure contour map of the White Pine area. This map shows all of the holes drilled at White Pine between 1937 and 1950. Individual holes are shown on the other maps (Figs. 4, 9, 10, 11) only if they provided data used in the construction of that particular map.

the map area. On the northeast side of the fault the position of the base of the Nonesuch shale is accurately known from drilling from one limb of the Iron River syncline to the other; the structure contours on Figure 7 depict its subsurface topography with greater or less assurance as the drilling is dense or sparse.

Immediately southwest of the White Pine fault, the position of the base of the Nonesuch shale is known at few points. It has been located by drill holes

at the old White Pine mine and northwest of that mine at the western edge of the area of Figure 7. The outcrop of the base of the formation, as shown in sec. 23, T. 50 N., R. 42 W. (Fig. 7), is based on a tenuous projection from two drill holes farther southwest, and may be in error by as much as half a mile. But even allowing for an error of this magnitude, the White Pine fault must be primarily a right-hand [3] tear fault. The horizontal component of slip along the fault would amount to over a mile, and the vertical component may not be more than a few hundred feet.

Anticline.—The structure contours of Figure 7 show the prominent anticline northeast of the fault. In this fold, which is probably representative of many folds that are due to drag on faults, the curvature increases at an accelerating rate toward the fault. Along a horizontal line through the Schacht shaft, at right angles to the fault trace, the rate of change of dip is about 1° per 1,000 feet at 9,000 feet from the White Pine fault, 1° per 500 feet at 6,000 feet, 1° per 150 feet at 3,000 feet, and about 1° per 80 feet at 2,000 feet. Presumably the rate of change of dip decreases at a similar rate southwest of the fault in a synclinal fold.

The crestline of the fold shows several irregularities (Fig. 7). From a slight dome northeast of the Schacht shaft the crest descends southeastward to a prominent saddle in section 14, T. 50 N., R. 42 W. This saddle represents the intersection of the anticline with the trough of the Iron River syncline. The amount of drilling southeast of the saddle is insufficient to properly define the structure near the southeastern outcrop.

In the northeastern part of the drilled area the rocks dip northeast at a relatively uniform angle of about 10°. The fold proper should probably be regarded as ending at about 10,000 feet from the fault, where the curvature of the bedding measured in sections striking northeast becomes negligible.

Minor Faults.—The minor faults of the White Pine area have been a subject of special concern because of speculation about their effect on mining operations. They also have a bearing on the interpretation of copper distribution as recorded in drill holes. It is shown in the following that the minor faults are related to the White Pine fault, and that they, like the curvature of beds in the White Pine anticline, decrease in magnitude away from the White Pine fault. This decrease provides the basis for a test of the relationship of copper distribution to structure, discussed in a later section.

The faults exposed in the drifts at the Schacht shaft strike between N 20° E and N 50° W and have dips between 70° W and 60° E. Most strike a little west of north and dip more than 80°, either east or west. The vertical component of slip on practically all faults shows normal-fault movement and ranges in magnitude from less than a foot to about 35 feet. More than half of the faults, however, are primarily strike-slip faults. Those with right-hand slip have an average strike of N 33° W, and those with left-hand slip an average strike of N 15° W. This difference in strike suggests that the two sets may represent complementary shears so disposed that the axis of principal shortening lies in the acute angle between them, or somewhere near N 25° W.

[3] As used here, "right-hand" movement means that the displacement of the block across the fault from the observer is to the right as he faces the fault.

This orientation is consistent with right-hand movement on the main White Pine fault (Fig. 7).

Maps of the old White Pine mine reveal a tendency for faults to trend more and more westerly as they are followed toward the White Pine fault; the fault in the southeast corner of section 9 (Fig. 7) has been curved to show the resulting hook-shaped pattern on the assumption that the habit persists away from the old mine. This curvature in plan also suggests right-hand movement on the White Pine fault.

The minor faults are clearly related to the White Pine fault in frequency as well as habit. The frequency of faults encountered in the mile-long drift at the Schacht shaft (Fig. 7) bears a very simple empirical relation to the magnitude of their vertical stratigraphic displacements. The average distance between faults with more than any given displacement is approximately 100 times the given displacement. For example, in a drift more or less parallel to the White Pine fault and 1,500 feet from it (the average distance of the Schacht shaft drift), faults with more than 10 feet of vertical displacement may be expected about every 1,000 feet, and faults with more than 1 foot of vertical displacement may be expected every 100 feet.

Faulting was much more intense in the old White Pine mine, which is considerably closer to the White Pine fault. Along a line 600 feet from the fault the average distance between minor faults with more than a given vertical displacement is only about 24 times the average displacement. At 500 feet the factor is about 18; at 400 feet, 14; at 300 feet, 12; and at 200 feet, 10. These empirical factors for the old mine are based primarily on the larger faults with displacements of over 5 or 10 feet as shown on an unpublished map of that mine by Dr. T. M. Broderick.

Summarizing the data on minor faults in the White Pine area, most of the faults seem to be characterized by strikewise movement. Two complementary sets of such faults may be identified, and they suggest an axis of shortening oriented about N 25° W; this is compatible with dominant right-handed strikewise movement on the White Pine fault. The tendency of minor faults to hook westward in plan as they approach the White Pine fault is likewise attributed to right-handed drag on the fault. Finally, the frequency and magnitude of minor faults decrease progressively away from the White Pine fault. The minor faults within several thousand feet of the White Pine fault, therefore, are clearly offspring in a sense of this major fault.

The progressive decrease in frequency of fractures away from the fault is paralleled by a progressive decrease, described earlier, in the rate of change of dip of the beds (i.e., a decrease in the amount of curvature). At any place the abundance and average displacement of faults are probably in fairly direct ratio to the amount of local curvature indicated by the contours of Figure 7. There are probably few faults of any consequence in the northeastern part of the area, and the greatest number should be expected on the southwestern limb of the anticline. The sharp change in dip in sec. 24 (Fig. 7) probably indicates strong faulting. The S-shaped curve in the sea-level contour in sections 11 and 14 suggests more faulting than might be expected this far from

the fault, as does the dome on the crest of the anticline just northeast of the Schacht shaft.

GEOLOGY OF THE COPPER MINERALS AND RELATED MINERALS

The principal copper minerals in the lowermost Nonesuch shale over the area drilled at White Pine are chalcocite and native copper. Bornite, covellite, and chalcopyrite are present only in infinitesimal quantities. A very small amount of native silver is generally present with the copper minerals, and pyrite was locally noted in fissures and in certain layers in and above the cupriferous zone.

Relative Abundance of Minerals

The proportions of the principal minerals show considerable variation. In mill concentrates from the old White Pine mine, sampled in 1918, 98 percent of the copper was native, and 2 percent occurred as sulfide (3, p. 106). These concentrates presumably came from the upper and lower sandstones, the ore horizons in the old mine; these horizons are almost barren over most of the area explored by the Copper Range Co. In recent pilot-mill flotation feed of parting shale from the Schacht shaft McLeod (8) established by extensive grain counts that 87 percent of the copper occurs as chalcocite and only 13 percent as native copper.

Analyses for sulfur as well as copper were made by the Copper Range Co. on samples from a number of scattered drill holes mostly located in sections 3, 4, and the northern half of 10, T. 50 N., R. 42 W. (Fig. 7). The stratigraphic units sampled are comparable in about 20 holes. These analyses indicate that the amount of sulfur, by weight, generally ranges from 18 to 23 percent of the amount of copper in the parting shale, from 20 to over 40 percent in the upper sandstone, and from 20 to 30 percent in the upper shale. In general the proportion of sulfur increases towards the east in the shale beds; the analyses of the upper sandstone do not show a clear trend. The weight of sulfur is about 25 percent of the weight of the copper in chalcocite, so these analyses indicate a high ratio of chalcocite to native copper throughout the area sampled, and sulfur in excess of that required for chalcocite in some individual samples, particularly in the upper sandstone. This excess is due in part, if not wholly, to pyrite, which can be seen megascopically in some of the cores that show excess sulfur.

In general an eastward increase in sulfur content relative to copper can be at least qualitatively recognized in the drill core itself. For example, in the upper shale along the line of section A-A′ (Fig. 5), native copper was seen only in the two most northwesterly holes, and pyrite is prominent in drill holes 2-G, 4-I, and 5-J.

McLeod's (8) study of pilot mill products from parting shale at the Schacht shaft indicates that copper sulfides other than chalcocite are quantitatively negligible there. Extensive grain counts did not disclose measurable quantities in the flotation feed. In the concentrates, there was enough to determine that about 0.0014 percent of the copper occurs as bornite, 0.0010

percent as covellite, and 0.0005 percent as chalcopyrite. Traces of chalcopyrite and bornite, but not covellite, have been seen underground and in drill core; they occur as fillings in fissures.

Silver, largely if not wholly in the form of native metal, is everywhere a trace constituent of the copper-bearing rocks. The top of the lower sandstone was mined for native silver a little north of White Pine at the localities marked D, E, F, and G in Figure 1, and elsewhere in their vicinity, during a short-lived boom from 1872 to 1875, described by Rominger (11, p. 153–159), Whittlesey (15), and Jamison (6, p. 183–193).

The Copper Range Co. made assays for silver on the same samples that were analyzed for sulfur. The analyses from 22 drill holes show that the ratio of silver to copper is generally highest in the parting shale (silver equals 0.08 percent of copper), intermediate in the upper shale (0.03 percent), and lowest in the upper sandstone (0.02 percent). Holes with high and low silver content are interspersed irregularly over the area sampled, and there seems to be no systematic areal variation in silver content or the ratio of silver to copper.

Pyrite was noted in a number of drill cores from White Pine. It occurs particularly in the laminated siltstone and shale 6 to 9 feet above the upper sandstone in the eastern part of the drilled area, where this stratigraphic zone is not copper-bearing. Traces are also visible megascopically in many cores from the striped bed, still higher stratigraphically. The pyrite has the form of tiny cubes, mostly 0.02 to 0.07 mm. across. These cubes occur as disseminated grains, or in clusters a millimeter or two across; pyrite may make up from 10 to 75 percent of the material in any given cluster (the remainder is siltstone or shale), depending on how closely spaced the individual cubes happen to be.

Stratigraphy of Copper Distribution

The areal distribution of copper in the various beds of the parting and upper shales can be roughly correlated with variations in the lithology and thickness of the beds. In general the lines of equal copper content are independent of structure; they trend northeast, more or less parallel to isopachs and facies boundaries. Copper in the upper and lower sandstones, on the other hand, is clearly most abundant near the White Pine fault.

Chalcocite and native copper occur principally as fine disseminations in shale, siltstone, and sandstone, and to a lesser extent as thin seams on joints or bedding planes and as vein minerals on faults. Chalcocite, in addition, forms small nodular masses up to several millimeters in diameter occurring individually or in groups in bedding planes; the nodules grouped in bedding planes resemble beads strung loosely together when viewed in cross section.

The abundance of these copper minerals varies systematically and strikingly from bed to bed. Figure 8 shows the assay data for the cupriferous zone in 10 holes from the western ends of sections A-A′ and B-B′ (Fig. 5). The sampling was done by others before the writers studied the lithology of the core, and individual samples may actually represent the rock a few inches higher or lower than the diagram shows; but the amount of such error is probably less than 3 inches at most places. As the figure shows, the stratigraphic

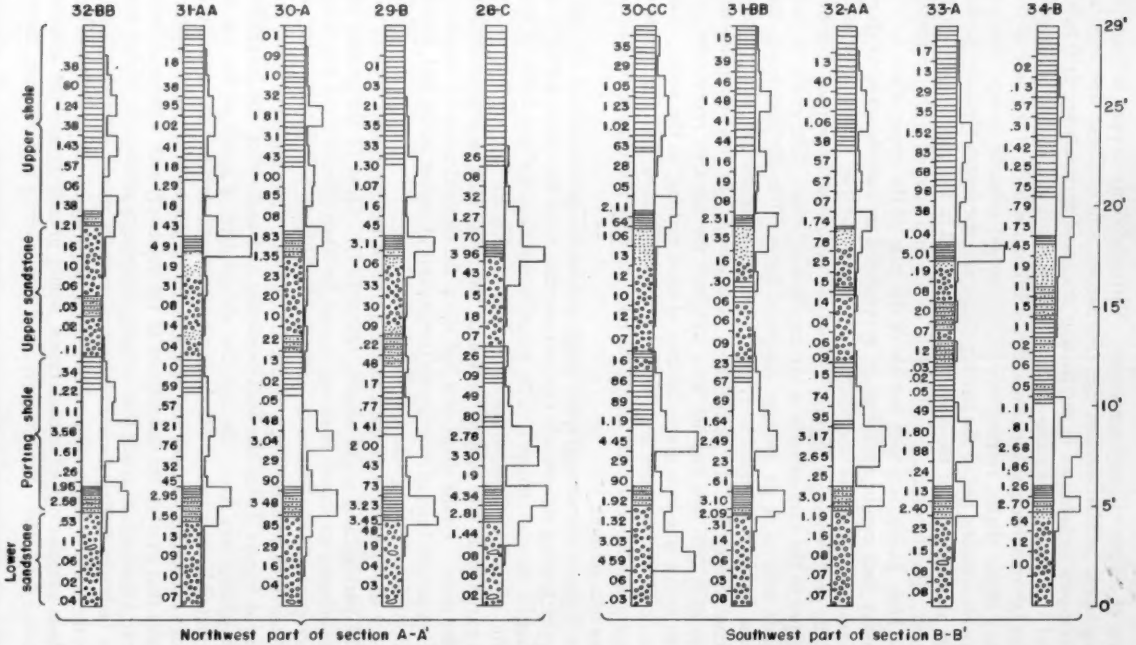


FIG. 8. Typical stratigraphic sections at White Pine. Copper content (percent) shown graphically and numerically. Lithologic symbols are as follows: lines, interlaminated siltstone and shale (close spacing of lines indicates fine laminae); dots, very fine to fine-grained sandstone; circles, medium- to coarse-grained sandstone. Individual drill holes are approximately 1,440 feet apart; see Figs. 5 and 7 for location of sections.

localization of copper [4] is very consistent. Virtually all the copper is found in five stratigraphic subdivisions of the cupriferous zone. These five copper-bearing subzones include two in the parting shale and three above; drill holes 32-BB and 31-BB best typify this distribution. Counting up from the bottom, the first and third subzones coincide with the laminated beds at the base of the parting and upper shales, respectively. The second subzone is near the top of the massive siltstone bed in the parting shale, and the fourth typically occurs in and just above the top of the massive siltstone bed in the upper shale. The fifth subzone, absent in some places (Hole 28-C) and merged with the fourth in others (Hole 34-B), is 6 to 8 feet above the base of the upper shale.

The assay data can be combined or represented in various ways to show the stratigraphic and areal distribution of copper for the drilled area as a whole. The grade curve in Figure 3 shows the typical stratigraphic distribution of copper in the various beds of the cupriferous zone. The grade of each stratigraphic interval is an average computed from 60 to 80 drill holes, but because this figure is intended to typify rather than summarize, this average is not a true average for the drilled area as a whole. In the first place the grade from each drill hole has not been weighted for the area represented by the hole, so undue weight is given the area of most drilling, to the west. And second, some of the subzones are absent in part of the area (see Fig. 5), and the average grade has not been diluted to take the very low copper content of these areas into account.

Figure 5 shows the stratigraphic range and lateral persistence of the individual copper-bearing subzones in two sections that cross the entire drilled area at right angles to one another. The actual assay data for five holes at the western end of each of these sections are shown in Figure 8.

Areal variation in the copper content of the rocks may be represented in at least two ways. Grade maps of a bed show the concentration of copper in that bed. A second kind of map shows the amount of copper in the bed, which is a function of both the grade and the thickness.

Figure 9 shows areal variations in the grade of the laminated beds at the base of the parting and upper shales, respectively. Most of the grades on which the contours are based, however, cannot be taken directly from the assay data, because sample boundaries do not coincide with the top, in particular, of the laminated beds in a majority of the drill holes. It is apparent from the histograms of Figure 8 that the beds overlying and underlying the laminated beds are typically very lean. In fact, the abrupt drop in grade at the top of these laminated beds is one of the most persistent and uniform characteristics of assay logs of channel samples and drill core in the White Pine area. Therefore samples that overlap the boundaries of the relatively rich laminated beds will have an intermediate grade that actually represents neither the richer nor the leaner bed. Including these overlapping samples would inevitably lower the apparent grade of the laminated beds in a majority of the drill holes, but leaving these samples out of consideration would greatly reduce the amount of information available. For the purpose of constructing a grade map, there-

[4] "Copper," unless prefixed by "native," includes copper in chalcocite as well as native copper.

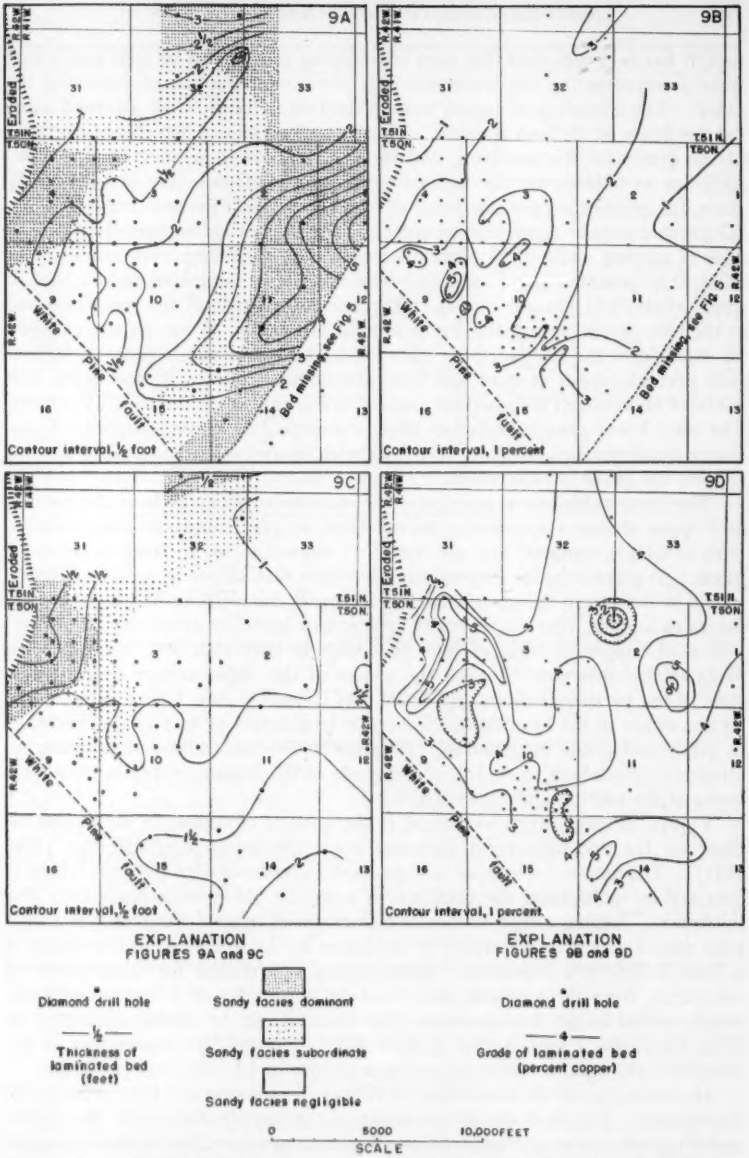


FIG. 9. Lithology, thickness, and grades of laminated beds: A. Lithology and thickness of laminated bed at base of parting shale; B. Grade (percent copper) of laminated bed at base of parting shale; C. Lithology and thickness of laminated bed at base of upper shale; D. Grade (percent copper) of laminated bed at base of upper shale.

fore, it has been assumed that each overlapping sample can be split into a rich fraction representing the laminated bed, and a lean fraction representing the other. The allocation of copper to each fraction is based on an assumed value for the grade of the lean fraction. These assumed values, which are averages of the grades of the overlying and underlying beds in nonoverlapping samples, are as follows for the various beds: (1) sandstone just below parting shale, 0.5 percent copper northeast of crest of White Pine anticline (Fig. 7), 0.7 percent copper southwest of crest; (2) first foot above laminated bed at base of parting shale, 0.35 percent copper; (3) sandstone just below upper shale, 0.57 percent copper; and (4) first foot above laminated bed at base of upper shale, 0.31 percent copper. The estimated grade of the laminated bed at the base of the parting shale in drill hole 34-B (Fig. 8) can be estimated as an example of the computation. The 1-foot sample with a copper content of 1.26 percent copper is only half from the laminated bed. If the upper half contains an assumed 0.35 percent copper, the lower half contains 2.17 percent. The next lower sample, 9 inches thick, contains 2.70 percent copper. Combining these two samples gives 15 inches with an average grade of 2.49 percent copper, the grade used in preparing Figure 9B.

The three subzones in and above the massive siltstone beds of the parting and upper shales, respectively, do not have simple boundaries that coincide with lithologic contacts, and are therefore more difficult to treat in terms of grade. A given subzone may be patently richer than others in some drill holes, as can be seen from the sample data of Figure 8, but without lithologic boundaries as a guide, there is no really satisfactory basis for determing the distribution of copper in samples that may include both rich and lean material. Most of the difference between the assays of the upper copper-bearing subzone of the parting shale in drill holes 30-CC and 32-AA, for example, could be due either to the location of the sample boundaries or to actual differences in grade and grade distribution. Because of this and related difficulties, no attempt is made here to represent the grade of the higher copper-bearing subzones of the parting and upper shales.

Figure 10 shows areal variations in the amount of copper in each subzone. Data for the two uppermost subzones are combined in a single map (Fig. 10D). The amount of copper is expressed in terms of foot-percent, which is obtained by multiplying the thickness of a unit by its average grade over this thickness. Adding a foot or two of lean material beyond the limits of a subzone makes very little difference in the figure for foot-percent, so the choice of a limit is not very important. Foot-percent was chosen for convenience of calculation from the available data, because the grades of 1-foot samples are simply added to get foot-percent. But the unit can be readily converted to other measures; 1 foot-percent is equal to 1.67 pounds per square foot or 8.1 kilograms per square meter, assuming a density of 12 cubic feet per ton.

In summary, the characteristics of copper distribution are here recorded in five figures. Figure 8 shows specimens of the sample data; both this figure and the grade curve of Figure 3 show the stratigraphic distribution of copper typical of the western part of the drilled area. Figure 5 shows the lateral persistence of the copper-bearing subzones as stratigraphic units. Figure 9 re-

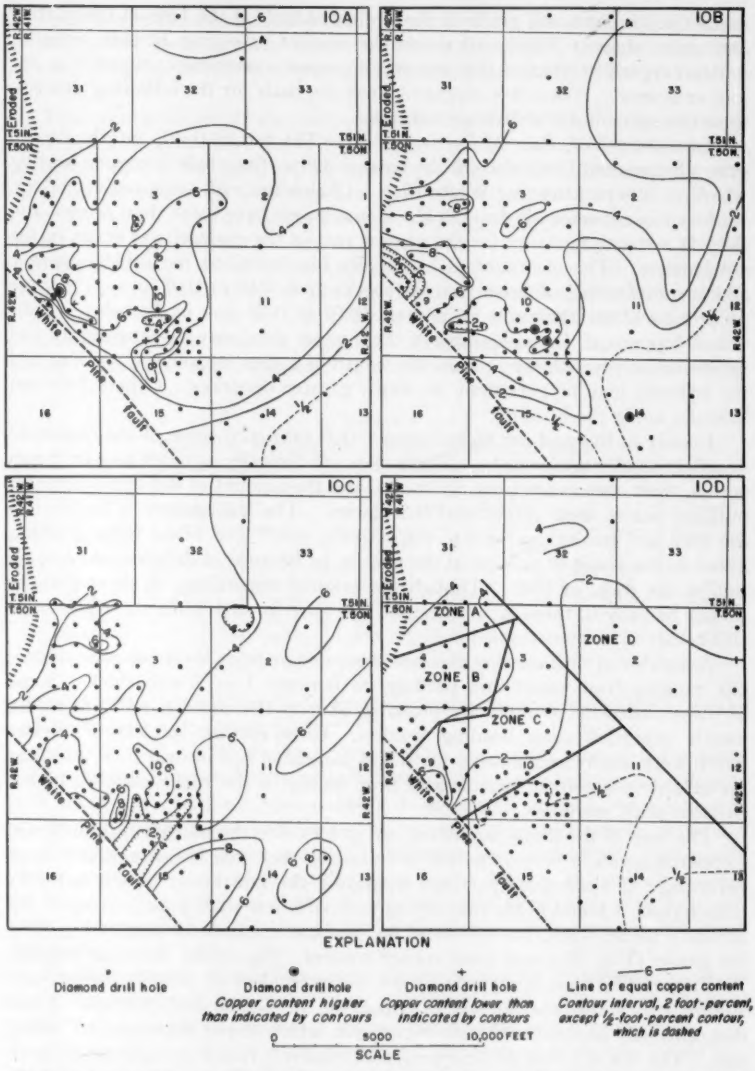


FIG. 10. Amount of copper in subdivisions of the cupriferous zone: A. Thinly laminated unit at the base of the parting shale, including copper in lean foot immediately above; B. Massive siltstone unit in the middle of the parting shale, including all copper in parting shale not shown in Fig. 10-A; C. Thinly laminated unit at the base of the upper shale, including copper in lean foot immediately above; D. Massive siltstone and overlying evenly laminated siltstone and shale of the upper shale. Zones A, B, C, and D referred to in text.

cords the thickness and grade of the laminated beds at the base of the parting and upper shales. Figure 10 shows the amount of copper in each subzone, without regard to whether this amount of copper is contained primarily in one foot or several. These five diagrams form the basis for the following descriptions of copper in the individual subzones.

Laminated Bed, Base of Parting Shale.—The bed of thinly interlaminated gray siltstone and black shale at the base of the parting shale is copper bearing wherever it is present near White Pine. Chalcocite, with some native copper, is finely disseminated all through it. Some layers have more than others, and there is a strong tendency for the greater part of the chalcocite to occur in the silt laminae. The chalcocite is essentially interstitial to the lithic minerals, and of comparable grain size (minute specks up to 0.04 or 0.05 mm). A large proportion of the chalcocite is in grains 0.01 to 0.03 mm in diameter. Individual copper-rich laminae, many of them paper thin, may be consistently and rather uniformly rich for at least the length of a thin or polished section, and the richness may be persistent for much greater distances. Others fade out laterally along the bedding.

Locally in this and the higher copper-rich subzones, some of the chalcocite occurs in small nodular clots. These clots are typically as much as 4 or 5 mm across, their centers are pure chalcocite, and the amount of impurity increases outward across their gradational boundaries. The laminations of the enclosing rock are bent up and down, respectively, above and below these nodules, either as the result of growth of the nodule, or because of differential compaction of the rock, or both. Though the original mineralogy of these nodules cannot be proved, there is no question that they formed while the rocks were still relatively unconsolidated.

A number of drill cores of this bed show one or more layers of pure chalcocite ranging from paper-thin partings to laminae 1 or 2 mm thick. Some of these chalcocite partings are probably akin to the nodules, and others are clearly postlithification bedding veinlets. Cross-cutting veinlets of similar width were locally seen cutting the thinly laminated bed in drill core, and they are relatively common, particularly near faults, in the rocks exposed in the Schacht shaft workings.

The base of the thinly laminated bed grades into the underlying sandstone. Copper is typically very abundant in transition rock that has a relatively large percentage of black-shale partings separating the thin sandy layers, but very little copper is found in the underlying rock with few such shale partings. By the same token, where the laminated bed becomes excessively sandy (Fig. 9A) the grade (Fig. 9B) and total copper content (Fig. 10A) decrease notably.

Figure 9B shows the grade of the laminated bed in percent copper, and Figure 10A shows the amount of copper in the bed in foot percent. These diagrams may be compared with Figure 9A, which shows thickness and lithology. The bed is 1.5 to 2.5 feet thick and relatively free from laminae of sand-size material ($\frac{1}{16}$ mm to 2 mm) in a lobate area trending northeast across the center of the map area. The bed is also richest in this area (Fig. 9B). Because the bed gradually thickens eastward, the total amount of copper (Fig. 10A) is highest a little east of the richest portion. And though the grade is

typically low in the exceptionally sandy material of the easternmost part of the area (The bed there is really sandstone with a few shaly partings.), the total amount of copper is moderately large because of the greater thickness of the bed.

This laminated bed at the base of the parting shale shows better than any other bed a close correlation between copper content and the depositional environment of the bed itself. The sandstone "high" that interrupts the continuity of the bed to the southeast (see drill hole 5-J, Fig. 5) trends northeast (Fig. 9A). The area of richest and most abundant copper lies down the slope northwest of this "high," and has its longest dimension parallel to the "high." The northeastward trend of the rich area, therefore, is parallel to paleogeographic features that existed at the begining of Nonesuch time. It is at right angles to the White Pine fault and the crest of its associated anticline, instead of parallel to them as might be expected if structural control determined distribution of copper. And richness is almost inversely proportional to sandiness,

TABLE 1

COPPER IN MASSIVE BED, MIDDLE OF PARTING SHALE

Distance base of massive bed to first reddish layer above massive bed (feet)	Number of holes	Grade (percent copper) for various intervals (feet) above base massive bed					Total copper (ft-percent)
		0–1	1–2	2–3	3–4	4–5	
5¼–6	22	0.44	1.29	2.28	1.33	0.69	6.03[5]
4¼–5	30	0.65	1.49	1.68	0.95	0.56	5.33
3¼–4	10	0.38	0.82	1.75	0.77		3.72
2¼–3	7	0.27	0.59	1.07			1.93

a condition that should hardly be characteristic if primary permeability of the bed itself were a dominant factor.

Massive Bed, Middle Parting Shale.—The gray upper part of the massive bed in the middle of the parting shale is typically copper bearing. Chalcocite with subordinate native copper is finely disseminated through the siltstone in grains comparable in size with the detrital grains, principally quartz, that make up the rock. Some of the grains of chalcocite look interstitial, particularly where groups of more or less contiguous grains form a skeletal clot within the rock. Other grains of chalcocite, on the other hand, look very little different in shape and disposition from the detrital grains of quartz and other materials.

Nodular masses of relatively pure chalcocite similar or identical to those in the laminated bed below are found also in this bed. Most of the rock is massive, and divergence of layers around the nodules was not observed.

The typical stratigraphic and geographic distribution of copper within this subzone is shown quantitatively by the assay data. Table 1 is a tabulation of the average grade, in percent of copper, of each foot above the base of the massive bed. The average grade and total copper content vary with the thickness

[5] About 6.5 foot-percent if interval 5–6 feet is included.

of the massive bed plus the gray laminated shale and siltstone above it; the data of the table are arranged in order of decreasing values for this stratigraphic thickness. The rock with reddish laminae that overlies this subzone typically contains less than 0.2 to 0.3 per cent copper.

The table shows that rock from 2 to 3 feet above the base contains the most copper (30 to 55 percent of the copper in the bed), regardless of the distance to the reddish rock above, and that the bottom foot, a reddish siltstone, has very little.

Averages such as those in Table 1 could conceal considerable variation in the actual position of the peak grade from place to place, but actually the variation is not great. The average position of the peak grade in 61 holes is 2.4 feet above the base, and the standard deviation is only 0.5 foot. Both the distribution of average grades (Table 1) and the relative constancy of the position of the peak grade bespeak a very uniform stratigraphic distribution of the copper.

As can be seen in Figures 5 and 8, the position of this copper-bearing subzone is about the same whether the base of the lowest overlying laminated gray siltstone and dark gray shale is 2 or 5 feet above the base of the massive siltstone bed. This suggests that deposition of copper is independent of the degree of lamination of the rock.

The areal distribution of copper in the middle of the parting shale is shown in Figure 10B. The thickness of massive gray siltstone and the overlying gray laminated siltstone and shale is greatest (Fig. 5) and the copper in this bed most abundant in the westernmost part of the area. The water is presumed to have been deeper in this vicinity than in other parts of the area during the early part, at least, of the deposition of the massive bed (Fig. 5). Where the massive bed becomes entirely reddish (e.g., Hole 5-J, Fig. 5) it contains no copper.

Laminated Bed, Base of Upper Shale.—The thinly laminated bed at the base of the upper shale is similar in copper content, as well as lithology, to the bed at the base of the parting shale. Chalcocite and native copper have essentially the same mode of occurrence in both beds. According to the ratio of the two minerals, as computed from analyses for sulfur, most of the native copper in the upper shale occurs in the westernmost mile or less of the area; megascopically visible native copper is far less abundant than chalcocite even there.

Figure 9D shows the grade of the laminated bed at the base of the upper shale in percent copper, and Figure 10C shows the amount of copper in the bed in foot-percent. These diagrams may be compared with Figure 9C, which shows the thickness and lithology of the bed, and with Figure 4, which shows the thickness and lithology of the underlying upper sandstone. There is no such striking correlation in detail between copper distribution and sedimentary facies as was noted in the laminated bed at the base of the parting shale, but the following correlations may be noted. The bed is very thin but rich in a narrow belt just east of the area in which it consists predominantly of sandstone laminae (Fig. 9C). Another narrow belt of richer rock seems to follow the eastern margin of the area of subordinate sandstone

laminae in secs. 3 and 10, T. 50 N., R. 42 W. The most extensive areas of rich rock, however, are in the easternmost part of the area; because the bed is also thickest in this vicinity (Fig. 9C), the total amount of copper (Fig. 10C) is much greater than that which characterizes the western half of the area. Most of this eastern area lies well down the southeastern slope of an upper sandstone delta tongue (Figs. 4 and 5).

Here, as in the laminated bed at the base of the parting shale, therefore, the most abundant copper seems to occur in a place that received a thick deposit of laminated siltstone and shale, down the slope from a "high" in the underlying sandstone. It is interesting to note (Fig. 5) that outpouring of the upper sandstone seems to have completely changed the position of high and low places, and that the areas of high copper content go with the low places in the beds above both sandstones.

Copper in and above Massive Bed, Upper Shale.—Copper is found from 2 to 8 feet above the base of the upper shale. It occurs primarily as disseminated chalcocite and as chalcocite nodules, as in the lower copper-bearing subzones. Over a limited part of the White Pine area (Zone B in Fig. 10D),

TABLE 2

COPPER IN MASSIVE AND HIGHER BEDS, UPPER SHALE

Zone[1]	No. of holes	Grade (percent copper) for various intervals (feet) above base of the massive bed						
		0–1	1–2	2–3	3–4	4–5	5–6	6–7
A	9	0.29	0.29	0.95	1.11	1.04	0.75	0.49
B	19	0.19	0.34	0.92	0.79	0.61	1.06	0.72
C	21	0.28	0.33	0.92	0.91	0.41	0.32	0.10
D	12	0.12	0.23	0.80	0.61	0.46	0.26	0.07

there are two distinct copper-rich layers, both recognizable in the assays of several drill holes in Figure 8 and in the grade curves of Figure 3; they are generally 2 to 4 and 5 to 7 feet, respectively, above the base of the massive siltstone bed. The lower concentration occurs at the top of the massive siltstone bed and extends a little higher into the overlying interlaminated gray siltstone and shale; the upper concentration occurs entirely in this interlaminated siltstone and shale.

In Zone A (Fig. 10D), northwest of Zone B, these two copper concentrations seem to merge into a single subzone (drill hole 34-B, Fig. 8). The uppermost copper-bearing subzone dies out southeast of Zone B (Fig. 10D, and section B-B′, Fig. 5) and is absent in Zone C. In several drill holes in Zone C and in the Schacht shaft, however, small amounts of pyrite occur in the same stratigraphic interval as the uppermost subzone; this pyrite occurs as small cubes, 0.02 to 0.07 mm across, disseminated or in clusters 1 to 2 mm across. The lower of the two subzones more or less disappears southwest of Zone C, and here, similarly, small amounts of pyrite were observed in some

[1] Zones labeled in Figure 10D.

drill holes in the same stratigraphic interval as the lower subzone. Most of the drill holes in Zone D (Fig. 10D) show a copper distribution like that of Zone C or A, but a few are like Zone B.

The assay data on these uppermost copper concentrations are summarized in Table 2. The data are segregated according to the various zones of Figure 10D. The stratigraphic characteristics of the copper distribution in the various zones as well as the limited vertical range of the individual copper concentrations are apparent from these figures.

The gradual eastward disappearance of copper in the two uppermost subzones does not appear to correlate with any recognizable change in the character of the enclosing beds. On the other hand, lines of equal total copper content (Fig. 10D) trend roughly northeast, like the axis of the upper sandstone delta (Fig. 4) and the isopachs of other beds (Figs. 9A, 9C); this at least suggests a closer dependence of copper content on the environment of deposition of the enclosing rocks than on the folds and faults of the area, which trend northwest.

Copper in Sandstone.—Chalcocite and native copper occur in the lower and upper sandstones, particularly southwest of the crest of the White Pine anticline. Native copper was dominant in the old White Pine mine, and chalcocite is more abundant over the area drilled by the Copper Range Co. In the drilled area, individual chalcocite grains or groups of grains are cleanly molded around and between the detrital grains; it is clear that the chalcocite has either filled interstitial voids or has replaced some sort of matrix, either another cementing mineral like calcite (which is abundant in these rocks) or fine-grained detrital material.

The general distribution of copper in the sandstone beds, unlike that of copper in the parting shale, yields a pattern that would be expected if the copper was deposited from solutions moving up the dip from the vicinity of the White Pine fault. Figure 11 shows the amount of copper in the upper 7 feet of the lower sandstone (Fig. 11A) and in the upper sandstone (Fig. 11B). The sample that contains the uppermost few inches of a sandstone bed is not reckoned in the total for that bed, in order to make sure that no copper from the rich overlying shale bed is included; the sample containing 1.44 percent copper at the top of the lower sandstone in drill hole 28-C (Fig. 8), for example, is not included. Drill hole 30-CC (Fig. 8) provides a good example of high copper content that is entirely and unequivocally in the lower sandstone.

Most of the holes with abundant copper in sandstone are near the White Pine fault, and all but one are southwest of the crest of the anticline. The native copper mined at the old White Pine mine (Fig. 11) came from the sandstones. Copper might be more abundant on this southwestern limb of the anticline because solutions rising along the sandstone beds from the fault would not tend to move beyond the crest and down the opposite limb; or it might be more abundant because this limb is more highly faulted and bent. Though more closely spaced information on copper and faults would be very desirable, Figure 11 shows no striking concentration of copper near the three known minor faults that are large enough to be detected from the

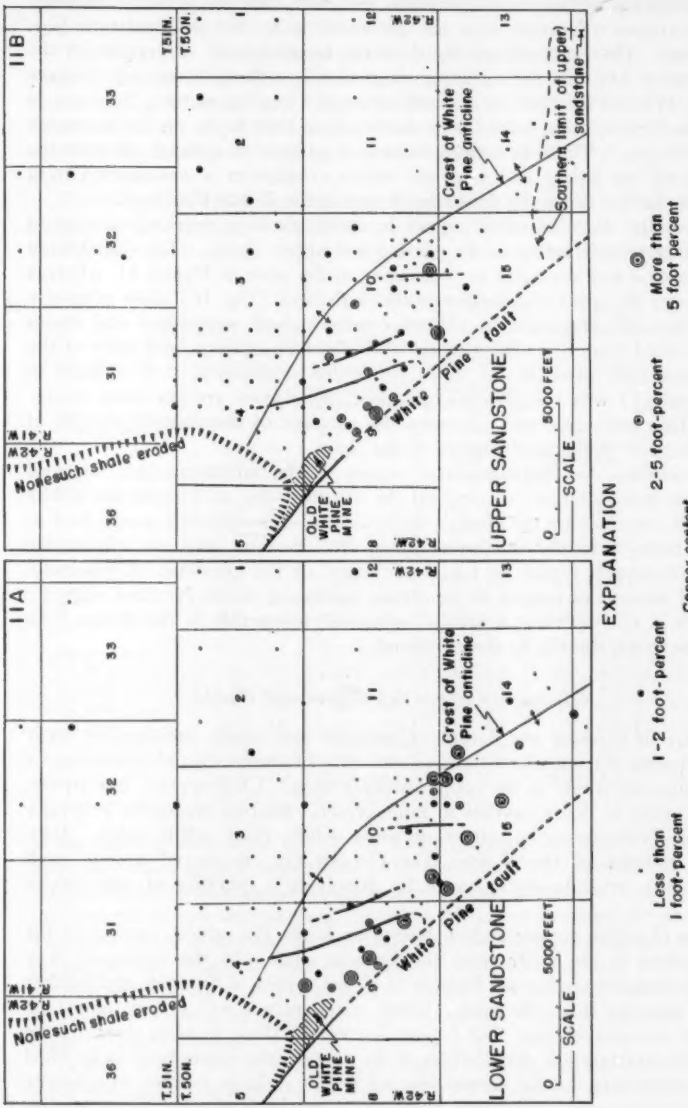


FIG. 11. Copper content of lower and upper sandstones.

drilling. One may tentatively conclude, therefore, that the principal channelways for copper migration were not the minor faults but the sandstone beds themselves. The apparent up-dip decrease in abundance of copper on the southwestern limb of the anticline may simply reflect increasing distance from the White Pine fault as a source of copper-bearing waters; the crest of the White Pine anticline would set a northeastern limit to the up-dip migration of these waters. There is nothing known at present to indicate whether the copper itself has a deep hydrothermal source or whether it was leached from shale beds farther down the dip or southwest of the White Pine fault.

The erratic distribution of copper in sandstone is in marked contrast to the more even distribution in the parting and upper shales. The distribution in sandstone is not amenable to contouring at the scale of Figure 11, whereas the contours of copper distribution in the shale beds (Fig. 10) show relatively few sharp peaks and hollows. If the copper in both sandstones and shales was deposited from the same general hydrothermal solution, and most of the actual flow took place in the more permeable sandstones, it is difficult to understand (1) why the patterns of copper distribution are not more similar in sandstone and shale and (2) why the patterns of distribution are not at least as regular in the sandstone as in the shale.

In summary, the distribution of copper in the sandstone beds suggests deposition from solutions moving up the dip from the vicinity of the White Pine fault; on reaching the crest of the anticline, such solutions would tend to migrate upward to the northwest along the crestline, and no appreciable amount of copper would be found northeast of the crestline. Conversely, the small amount of copper in sandstone northeast of the crestline suggests that there is no important source of solutions comparable to the White Pine fault zone down the dip to the northeast.

Relation of Copper to Fissures and Faults

Copper in Fissures and Joints.—Chalcocite and locally chalcopyrite occur as constituents of mineralized fissures, and films of chalcocite and native copper are common on joints in the copper-bearing beds. Chalcopyrite, like pyrite, tends to occur in drusy cavities in fault breccia, whereas chalcocite generally occurs in small masses or veinlets in more solidly filled calcite veins. John Rand, Geologist of the White Pine Copper Co., recovered a few small orthorhombic crystals of chalcocite by dissolving a quantity of vein calcite in acid.[7]

Films of native copper and chalcocite on joints are rather common in the parting shale in the drifts from the Schacht shaft. In the aggregate they probably contain only a small fraction of all the copper in the rock, and neither channel samples from the mine (which must include many such films) or drill-hole samples suggest that copper content of these veinlets disturbs the essentially stratigraphic distribution of the copper; the joints tend to be filled mainly where they cut the copper-bearing beds. A large number of specially chosen samples would be needed, however, to establish whether these veinlets

[7] J. Rand, oral communication.

are lateral secretions or whether they really represent copper introduced from some distance away.

Within a few feet of some of the larger faults that cross the Schacht shaft drifts, there are numerous thin veinlets of chalcocite in the top 2 or 3 feet of the lower sandstone. Not enough channel samples from the Schacht shaft include the uppermost foot or two of the lower sandstone, however, to estimate the amount—if any—of enrichment near faults that may be due to such veinlets.

Relation of Copper in Shale to Faults and Fissures.—The amount of copper in the parting shale in the Schacht shaft drifts is independent of proximity to faults or the amount of faulting. More than 250 channel samples

TABLE 3

COPPER IN PARTING SHALE VERSUS DISTANCE FROM FAULTS, SCHACHT SHAFT EXPLORATION

Distance from faults (feet)	Amount of copper (foot-percent) (Number of channels in parenthesis)				Standard deviation from average for exploration
	Northwest part	Middle part	Southeast part	Average for exploration	
Laminated bed					
0–2	(6) 5.4	(31) 6.5	(15) 6.8	(52) 6.5	2.2
2–4	(8) 7.5	(22) 6.4	(6) 6.5	(36) 6.6	2.4
4–8	(5) 8.1	(32) 6.5	(11) 7.8	(48) 7.0	2.4
8–16	(11) 6.2	(33) 6.0	(7) 7.0	(51) 6.2	2.4
16–32	(10) 6.9	(26) 6.5	(11) 7.6	(47) 6.8	2.5
32–64	(5) 8.5	(12) 5.4	(4) 6.6	(21) 6.3	2.6
Average	(45) 6.9	(156) 6.3	(54) 7.2	(255) 6.6	
Massive bed					
0–2	(5) 3.9	(31) 5.4	(15) 3.3	(51) 4.6	2.0
2–4	(8) 4.0	(24) 4.8	(6) 3.2	(38) 4.4	1.6
4–8	(5) 3.6	(32) 5.0	(9) 3.1	(46) 4.5	1.7
8–16	(11) 4.0	(35) 4.3	(7) 4.3	(53) 4.2	1.8
16–32	(10) 4.3	(29) 4.8	(11) 3.4	(50) 4.4	1.4
32–64	(4) 6.4	(10) 5.3	(5) 2.8	(19) 4.9	1.8
Average	(43) 4.2	(161) 4.9	(53) 3.4	(257) 4.5	

of the parting shale were cut by the Copper Range Co. at 20-foot intervals; each foot was assayed separately. The distribution of grades in practically every channel is such as to permit a very simple division of the total copper into two parts, one representing the lower laminated bed and the first foot of lean rock above it and the second including the copper in the balance of the parting shale. The lean rock just above the laminated bed is a conspicuous element in the assay record of almost all channel samples, and it actually makes very little difference in respect to total copper whether it is included with the upper or lower fraction.

Tables 3 and 4 give the average copper content, in foot-percent, of the lower and upper parts of the parting shale for groups of samples at different perpendicular distances from faults. Data are presented separately for three different parts of the Schacht shaft exploration, as well as for the exploration

as a whole. The unbracketed figures after "0–2" in each table, for example, give the mean copper content in foot-percent of the upper or lower unit in all the channels in the given part of the mine that are within 2 feet of a fault. Figures in parenthesis are the number of channels included in the average. Table 3 gives the data for distance of channel sample from any fault, including some gouge slips with practically no visible displacement; in Table 4 only faults with displacements of more than a foot, horizontal or vertical, are considered.

The differences in copper content between the various categories in Tables 3 and 4 are mostly small, except in the case of categories represented by only a few samples. And in general such differences as do exist are unsystematic.

TABLE 4

COPPER IN PARTING SHALE VERSUS DISTANCE FROM FAULTS WITH MORE THAN A FOOT OF DISPLACEMENT, SCHACHT SHAFT EXPLORATION

Distance from faults (feet)	Amount of copper (foot-percent) (Number of channels in parenthesis)				Standard deviation from average for exploration
	Northwest part	Middle part	Southeast part	Average for exploration	
Laminated bed					
0–2	(5) 6.3	(15) 6.8	(5) 5.6	(25) 6.5	2.1
2–4	(4) 9.0	(15) 6.3	(4) 6.3	(23) 6.7	2.7
4–8	(4) 8.1	(16) 6.0	(3) 7.0	(23) 6.5	2.4
8–16	(10) 6.7	(27) 5.9	(11) 6.3	(48) 6.1	2.3
16–32	(9) 7.7	(36) 6.4	(12) 7.6	(57) 6.8	2.2
32–64	(9) 7.2	(32) 6.2	(9) 8.5	(50) 6.8	2.6
64–128	(3) 1.4	(15) 6.3	(10) 7.4	(28) 6.2	2.6
Average	(44) 6.9	(156) 6.3	(54) 7.2	(254) 6.6	
Massive bed					
0–2	(4) 3.3	(14) 4.9	(5) 2.7	(23) 4.2	1.7
2–4	(4) 3.8	(14) 5.2	(4) 2.9	(22) 4.5	1.9
4–8	(4) 3.5	(18) 5.0	(3) 3.4	(25) 4.5	1.5
8–16	(10) 3.5	(28) 4.9	(11) 3.4	(49) 4.3	2.0
16–32	(9) 4.3	(36) 4.4	(12) 4.3	(57) 4.4	1.4
32–64	(9) 5.4	(33) 5.1	(8) 3.3	(50) 4.9	1.7
64–128	(3) 5.7	(16) 4.8	(10) 2.6	(29) 4.2	1.5
Average	(43) 4.2	(159) 4.9	(53) 3.4	(255) 4.5	

The only data that suggest any systematic variation are those from the upper part of the parting shale in the northwestern part of the exploration; there is a suggestion, particularly in Table 4, that the amount of copper increases away from faults, though there probably are not enough samples to make the trend very certain. With this possible exception, the data from the Schacht shaft provide no basis whatever for assuming any relation between copper content of the parting shale and faults—they indicate that, at least on a scale of tens of feet, the two are quite independent.

The percentage standard deviation of individual 1-foot samples of the same bed generally averages between 32 and 43 percent, which indicates rather marked variability, due either to sampling technique or to actual varia-

tion from place to place. Some pairs of 1-foot samples cut from the same spot disagreed by as much as 20 percent in a few cases. Such differences may be explained, in part at least, on the basis of accidental inclusion and exclusion of chalcocite nodules and veinlets.

A second method of evaluating the importance of faults and fissures in relation to copper content is through comparison of the copper content of the two parts of the parting shale in individual channels. If the copper content of the upper half of the bed in each channel as ordinate is plotted against the copper content of the lower half of the same channel as abscissa, a scatter diagram results. Enrichment or impoverishment near faults should create a tendency, at least, for the copper content of both parts of the parting shale to be either rich or poor in the same channel; this should lead to a cluster of points that is elongate in a direction away from the origin. A diagram of this sort that was prepared shows only a slight tendency for the copper to be high in one bed where it is low in the other; the low negative correlation coefficient for the two sets of figures, -0.214, expresses the same suggestion numerically. If there is any actual relationship between the amount of copper in the upper and lower parts of the parting shale, therefore, the relationship is not that which should be produced by enrichment near faults.

One mineralogical observation in the Schacht shaft also suggests a lack of correlation between faults and mineralization. Chalcocite occurs in the upper shale 6 to 8 feet above the upper sandstone in the westernmost part of the drilled area (Zones A and B, Fig. 10D), and pyrite occurs in the same stratigraphic interval farther east. Where the Schacht shaft itself cuts this bed only pyrite is present, but 1,000 feet farther west in an exposure in a drift the bed contains only chalcocite. The pyrite exposed in the shaft is adjacent to a large fault (shown cutting the shaft in Fig. 7), whereas the chalcocite farther west is as much as 80 feet from the nearest fault. If this phenomenon is explained on the basis of normal hydrothermal zoning away from faults, the regional distribution is anomalous; pyrite is more abundant in the upper shale far from the White Pine fault than near it and is found high in the stratigraphic column rather than low. If pyrite is regarded as a sedimentary mineral that is replaced by chalcocite, the copper being hydrothermally introduced, the presence of pyrite next to a large fault is anomalous. The local and regional relationships are consistent only if the mineralogy is unrelated to the faulting.

The influence of tectonic features can be at least tentatively evaluated for the area as a whole. As was shown in the section on structure, the intensity of deformation, as measured by the abundance and magnitude of faults and by the amount of curvature of beds in the White Pine anticline, definitely decreases northeastward away from the White Pine fault. Individual minor faults tend to strike about N 25° W. If copper content is related to structure, therefore, lines of equal copper content over the area as a whole should tend to show some sort of parallelism with the White Pine fault and anticline. In detail they might show parallelism with minor faults and have northwesterly trends.

The grade of the laminated bed at the base of the parting shale (Fig. 9B)

is richer in a few spots close to the White Pine fault than away from it; the large area with more than 2 percent copper, however, is not parallel to the fault at all but extends directly away from the fault for at least 3½ miles as a belt about 1½ miles wide. It crosses the crest of the White Pine anticline at right angles. Conceivably there may be some enrichment of the bed near the fault; the richness of the copper-bearing area as a whole, however, seems to be quite independent of structural control.

The areal distribution of grades in the laminated bed at the base of the upper shale (Fig. 9D) is far more erratic than that of the bed at the base of the parting shale. There is, however, no apparent close association of high copper content with either the White Pine fault or the White Pine anticline.

The other copper-bearing subzones are less easy to compare from place to place in terms of grade. The maps showing the total copper content of these beds (Figs. 10B and 9D), however, do not suggest any correlation between copper content and faults or folds.

More conclusive, perhaps, than the lack of correlation between structure and copper content in individual beds are the differences in the areal distribution of copper from bed to bed. Structural features like faults and folds should affect all the beds in a given area more or less equally. If, for example, one bed is next to a main feeding fissure in a certain drill hole, all should be, as a general rule. The grades and amounts of copper in the various beds should therefore have a tendency at least to show the same areal patterns of distribution. Perfect correlation cannot be expected, of course, because of differences in thickness and lithology of the host beds from place to place; but the actual correlation is so poor (Figs. 9 and 10) that structural control seems a most unlikely explanation for the present distribution of copper.

In summary, there is no discernible spatial relation of copper in the parting shale to fissures and faults in the Schacht shaft exploration. Similarly, over the drilled area as a whole the distribution of copper in the parting shale and upper shale does not show the complete dependence on structure that is so manifest in the upper and lower sandstones; only the lowermost laminated bed is richer on the southwest flank of the anticline, and much of this superiority may ultimately correlate with the sedimentary features of the beds themselves.

ORIGIN OF COPPER

The copper in siltstone and shale at White Pine is believed to be derived largely from the waters in which the beds themselves were laid down. It is probably more nearly diagenetic than syngenetic, as the chalcocite and some of the native copper may have been precipitated below the surface of the bottom muds or may have replaced primary sulfide; but the copper is believed to have been introduced before the rock was lithified, deeply buried, and deformed. The copper in sandstone on the other hand, particularly the native copper in the old White Pine mine, shows a definite relation to the structure of the area; this is believed to be hydrothermally redistributed copper, possibly derived in large part from the beds at the base of the Nonesuch shale on the

southwest side of the White Pine fault. The basis for these conclusions, largely developed in the foregoing sections, may be summarized as follows:

(1) Copper is found at exactly corresponding stratigraphic positions in the two sedimentary cycles recognized in the cupriferous zone.

(2) The stratigraphic range of high copper content in the individual copper-bearing beds is less than 2 feet, on the average, and is relatively uniform over areas measurable in square miles.

(3) Copper is closely related areally to the depositional environment of the beds that contain it. It occurs in areas that probably had relatively deeper water than their surroundings.

(4) Over the drilled area as a whole the copper does not occur primarily in the permeable sandstone beds. Copper is typically abundant in sandstone or sandy siltstone only within a few inches at most of dark-gray shaly material except locally on the southwestern flank of the White Pine anticline.

(5) In the laminated beds at the base of the parting and upper shales the copper content is less where sandstone laminae are abundant than where such laminae are subordinate. If permeability were important, the opposite should be true.

(6) Copper in massive siltstone in both parting and upper shales is consistently separated by barren rock of similar lithology from the copper-rich laminated beds below. If there were only a single thin cupriferous shale bed overlying a permeable sandstone (e.g., the German Kupferschiefer), one might regard the shale as a membrane that captured the copper, either physically or chemically, from upward coursing waters. But the alternation of copper-bearing and relatively barren beds at the base of the Nonesuch shale is far less readily explained on this basis.

(7) The distribution of copper in the shales and siltstones is not primarily controlled by proximity to the White Pine fault or by the minor faults and the anticline related to it. This is most manifest in the contrast between copper in the sandstone beds, which is largely restricted to the area between the White Pine fault and the anticlinal crest, and copper in the other beds, which shows no such restriction. Only one bed, the lowermost laminated bed, is richer on the southwest flank of the anticline than on the northeast, and it is not at all certain that even this extra richness is due entirely to structural position.

Summarizing the seven preceding arguments, the primary factors controlling the present distribution of copper in the siltstone and shale were stratigraphic and paleogeographic; permeability of the host rocks and structure have had relatively little influence over most of the area drilled by the Copper Range Co. At least three general theories of origin satisfy these conditions: (1) the copper was dropped into or precipitated within the original mud; (2) the copper, diffusing downward into the uppermost few inches of mud, replaced some primary constituent of the mud, perhaps iron sulfide or calcium carbonate; (3) the copper was introduced into the rocks after lithification and presumably deformation, and the loci of deposition were controlled to an extraordinary degree by the physical or chemical character of the host rocks.

The first two theories require that the copper be derived essentially from the waters in which the beds themselves were deposited, with the copper being deposited only at those times and places at which favorable bottom conditions existed. The third requires an exotic source, presumably in depth.

The first theory, precipitation of the copper on or within the mud of a foul bottom, provides the simplest explanation for the apparent stratigraphic control of its deposition. The second theory, replacement of a primary mineral (e.g., calcium carbonate or iron sulfide) in the foul-bottom mud, is not very different from the first in most respects. It is mentioned primarily because Deans (4, p. 350) has recently suggested that replacement textures in the Kupferschiefer may be primarily diagenetic; although no replacement textures have yet been recognized in preliminary petrographic study of the Nonesuch shale, the numerous points of similarity between the copper deposits in the Nonesuch shale and the Kupferschiefer imply similarity of origin (14).

The third theory requires that the copper be introduced into the rocks after lithification. This possible origin is not incompatible with most features of the stratigraphic distribution of copper if it is assumed that the channels of access have had remarkably little influence on the present distribution of copper, compared with the physical or chemical composition of the host beds themselves. The principal arguments against such an origin are the following:

(1) The most likely channelways for widespread hydrothermal introduction of copper are the more permeable sandstones. In view of the abundant copper found locally in sandstone near the White Pine fault (Fig. 11), it seems unlikely that the sandstones would be so nearly barren over most of the area if they had acted as channelways for all the copper now in shale.

(2) The physical or chemical property that might have controlled the deposition of copper cannot be readily identified. If selective replacement of a primary mineral is invoked, it is difficult to determine what that mineral may have been. Some of the chalcocite now has the form of nodules, and the bedding is bent up and down around these nodules, indicating that they formed before consolidation of the rock. Such nodules might originally have consisted of calcite or pyrite, both of which can still be found as nodules in some beds. But selective replacement of calcium carbonate cannot be invoked because some consistently lean or barren beds between copper-rich beds are everywhere calcareous. If pyrite is the replaced mineral, it is difficult to explain why pyrite in the upper shale next to a large fault in the Schacht shaft is unreplaced. And in those beds of the upper shale that contain pyrite in one place and chalcocite in another, the amount of megascopic pyrite in pyritic places is generally far less than the amount of megascopic chalcocite in other places.

It is equally difficult to determine what physical property of a sediment might have led to such delicate selective precipitation of copper minerals. Copper is found in a variety of rock types, ranging from shale to sandstone.

It is present in both laminated and massive siltstone. It does not typically occur in reddish beds, but on the other hand, it does not occur in all the gray rocks. The rocks above and below the highest copper-bearing bed in the upper shale appear to be lithologically identical with this bed in all respects but copper content.

It may be too early to deny the possibility that the copper was introduced long after deposition of the beds, but in general a theory that requires such delicate selective replacement or precipitation over many square miles, and such independence of control by structure or permeability, seems more strained than a theory holding the copper to be essentially sedimentary in origin.

COPPER IN THE NONESUCH SHALE IN OTHER AREAS

Copper is found in traces, at least, in practically every place where the base of the Nonesuch shale can be observed, from the Bad River near Mellen, Wis., to a point 10 miles southwest of Calumet, Mich., a distance of over 100 miles (Fig. 1). At many points the trace consists only of a little copper stain on joints or bedding planes within a few inches at most of the basal contact; in some of these rocks a few flecks of chalcocite or native copper can be seen. Most of the sections of Figure 6, on the other hand, show chalcocite in quantities that are readily visible megascopically in hand specimen, though the total amount of copper in foot-percent is much less than at White Pine.

Observations at these various localities, each designated by the letter symbols used on Figure 1 and 6, are briefly summarized as follows:

Locality A. Considerable copper stain in lower 8 to 10 feet and in sandstone just below marker bed.

B. Considerable chalcocite in sandstone below marker bed near a large fault; sandstone barren away from fault. This copper may represent leakage along the fault from the underlying cupriferous zone, which is not exposed here.

C. Chalcocite in thin shaly parting 54 feet below marker bed, and in several dark-gray shale beds from 81 to 100 feet below the marker bed.

D-G. Chalcocite in parting and upper shales as at White Pine but generally much leaner.

H. Native copper in sandstones as at old White Pine mine.

I-J. White Pine area.

K. No copper seen. A little pyrite in sandstone 0 to 1 inch below lowest shale exposed.

L. A few specks of chalcocite at base of shale.

M. Base not exposed, no copper minerals seen.

N. Considerable chalcocite in lowermost few inches of parting shale.

One additional locality should be mentioned. At the White Pine Extension exploration, 5 miles west of Nonesuch mine (H, Fig. 1), 4.8 feet of part-

ing shale averages 1.08 percent copper, and 5.7 feet of upper shale averages 0.6 percent copper (1, p. 59).

The copper content of the cupriferous zone seems to be greatest along the south flank of the Porcupine Mountains in a belt that probably extends west to include much, if not all, of the Presque Isle syncline. South of this belt, where the rocks below the marker bed are sandier (southeast end of section A-A′, Fig. 5), the amount of copper is far less; no copper was seen at Gates Creek and almost none at Rockland. North of White Pine, also, in an area with less sandstone (sections D, E, F, G, Fig. 6) that presumably lay farther off shore when the lowermost Nonesuch shale was deposited, the cupriferous zone is appreciably leaner than in the vicinity of White Pine. If the present outcrop of the Nonesuch shale (Fig. 1), excluding its loop around the Porcupine Mountains, is more or less parallel to the old shoreline that existed during Nonesuch deposition, then the belt most favorable for copper must generally lie far down the dip over the region as a whole; in general the facies exposed at the surface is sandy except around the Porcupine uplift. The doming of the Porcupine Mountain area is responsible for bringing this normally deep-lying facies to the level of the present surface in that area. If this facies reaches the surface at any other place, it must be in the area northeast of Greenland, Mich.

U. S. Geological Survey,
Washington, D. C.,
March 25, 1954

REFERENCES

1. Allen, R. C., 1918, Mineral resources of Michigan for 1917 and prior years: Michigan Geol. and Biol. Survey, Pub. 27 (Geol. Ser. 22).
2. Ayer, F. A., 1950, White Pine mine, potential major copper producer: Min. Cong. Jour., vol. 36, p. 26–30, 55.
3. Butler, B. S., Burbank, W. S., et al., 1929, The copper deposits of Michigan: U. S. Geol. Survey Prof. Paper 144.
4. Deans, T., 1950. The Kupferschiefer and the associated lead-zinc mineralization in the Permian of Silesia, Germany, and England: XVIII Internat. Geol. Cong. Rept., pt. 7, p. 340–351.
5. Irving, R. D., 1883, The copper-bearing rocks of Lake Superior: U. S. Geol. Survey Mon. 5, 464 p.
6. Jamison, J. K., 1948, This Ontonagon country: The Ontonagon Herald Co., Ontonagon, Michigan.
7. Lane, A. C., and Seaman, A. E., 1907, Notes on the geological section of Michigan, pt. 1. the pre-Ordovician: Jour. Geol., vol. 15, p. 680–695.
8. McLeod, B. H., 1952, Microscopic examination of pilot-plant products from White Pine ore: private report to White Pine Copper Co.
9. Nishio, Keijiro, 1919, Native copper and silver in the Nonesuch formation, Michigan: Econ. Geol., vol. 14, p. 324–334.
10. Ramsay, R. H., 1953, White Pine copper: Eng. and Min. Jour., vol. 154, p. 72–87.
11. Rominger, C. L., 1876, Observations on the Ontonagon silver-mining district and the slate quarries of Huron Bay: Michigan Geol. Survey, vol. 3, pt. 1, p. 151–166.
12. Rominger, C. L., 1895, Geological report on the Upper Peninsula of Michigan iron and copper regions: Michigan Geol. Survey, vol. 5, pt. 1, 179 p.
13. White, W. S., Cornwall, H. R., and Swanson, R. S., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: U. S. Geol. Survey Geol. Quadrangle Map.
14. White, W. S., 1953, The copper shales of Germany and Michigan (abstract): Econ. Geol., vol. 48, p. 631.
15. Whittlesey, Charles, 1877, Iron River silver district, south shore of Lake Superior: Eng. and Min. Jour., vol. 23, p. 254, 278–279.

THE MARGINAL LUMINESCENCE OF CERTAIN INTRUSIVE ROCKS AND HYDROTHERMAL ORE DEPOSITS[1]

DAVID J. McDOUGALL

ABSTRACT

Several types of luminescent phenomena (fluoresence, cryoluminescence and thermoluminescence) have sometimes been found to bear a close relationship to the margins of certain intrusive rock masses and hydrothermal ore deposits. The causes of the luminescence are believed to be trace elements or radioactivity. It is suggested that zones of thermoluminescence, marginal to hydrothermal ore deposits, may be of use as a guide to the location of ore bodies. This phenomenon can be readily induced by the simple test of heating specimens below a red heat in a dark room and making visual observations of its presence or absence.

INTRODUCTION

THE familiar phenomena of fluorescence and phosphorescence, along with the lesser-known pyroluminescence and triboluminescence, have often been observed in minerals. All are related to imperfections in the minerals and may be due to small amounts of trace elements; excess ions, or co-ordination groups of elements; or the effect of radioactivity on the internal structure of minerals. However, aside from a few restricted applications, such as prospecting for scheelite and the sorting of fluorescent ores, as at Franklin Furnace, the various luminescent phenomena have been of little practical use in any phase of geology or mining. On the other hand, when the basic causes of the phenomena are considered in relation to the emplacement and alteration of intrusive rocks and ore bodies and the alteration of the surrounding rocks due to intrusion, the possibility arises that the spatial arrangement of luminescent minerals can be of use in the search for ores of a hydrothermal origin. Further possible uses include the tracing of intrusive contacts and studies of the distribution of trace elements and radioactivity in rocks.

Briefly, since both radioactivity and trace elements are one of the prime reasons for the occurrence of luminescence, and often both have an intimate relationship to intrusive rocks and hydrothermal ore bodies, it should be expected that luminescent minerals should occur in a similar intimate relationship.

Some preliminary studies of the distribution of luminescence in and near several masses of intrusive rocks and hydrothermal ore deposits have been made by the writer, and the concept stated above of the relationship of luminescence to such bodies has been found to be true in many cases.

THEORETICAL CONSIDERATIONS

There are five essential requirements for the occurrence of luminescence in mineral phosphors:

[1] Published with the permission of the Deputy Minister of Mines of the Province of Quebec.

a) *A source of energy,* known as an "excitant," which can be any one of gamma radiations; x-rays; ultra-violet, visible and infra-red light; thermal radiations; or friction.

b) *A means of transporting the energy through the phosphor to a point of emission.* This may be considered as a type of "energy shield," or a mechanism whereby the absorbed energy is prevented from being emitted as heat, and can only be emitted as light.

c) *A point of emission,* which is generally termed a "luminescent center." In minerals these "centers" may be due to impurities such as hydrocarbons; coordination groups of some element; a stoichiometric excess of an ion; small amounts of a trace element; or lattice imperfections of the Schottkey or Frenkel type.

d) *An ionic type of bonding* in the mineral. Native elements, sulphides, and sulpho-salts are generally non-luminescent, whereas the majority of the other chemical groups of minerals, which includes most of the essential and accessory rock-forming minerals, may be luminescent under suitable conditions of activator and excitant. Some exceptions to this general rule are luminescent sphalerite and diamond, which have a homopolar type of bonding.

e) *Ability to absorb radiations.* In order for the mineral to absorb energy it must be "transparent" to the radiations of the excitant. In this connection, it may be noted that most minerals which are opaque to visible light are non-luminescent, whereas many of the non-opaque minerals are known sometimes to exhibit luminescence.

Those minerals having lattice imperfections of the Frenkel or Schottkey types differ from what may be designated by the general term of the "activator-type" in that the luminescence is associated with "holes" in the lattice, rather than with the addition of abnormal ions to the lattice. There is a very close relationship between the intensity of the luminescence resulting from these lattice imperfections, and the duration and intensity of exposure to radioactivity (3).[2]

Activators which form luminescent centers are of four general types. The first are coordination groups, such as the UO_2 groups of certain secondary uranium minerals. The second type are those in which there is a stoichiometric excess of an ion—tungsten in scheelite being an example. The third is that in which there is a diadochic replacement of elements in the mineral by a trace element, the replacement of calcium by manganese being a very common example. The fourth type is that in which the trace elements or ions occupy interstitial positions in the lattice, such as cesium in feldspars. The optimum amount of activator in the third type is of the order of 10 percent, whereas in the fourth type it is of the order of 0.1 percent. Quantities of activator in these last two types, which vary greatly from the optimum, may "quench" luminescence.

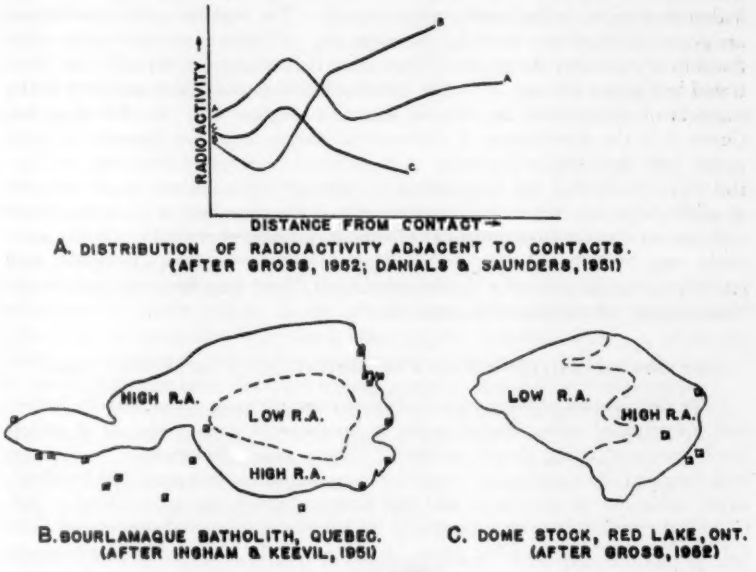
Quenching of luminescence is not restricted to excessively large or small amounts of activator, but may also result from "poisoning" by other elements.

[2] Numbers in parentheses refer to References at end of paper.

One of the commonest poisons is iron. Elevated temperatures will also serve as a quenching agent, by a temporary or permanent removal of the energy shield. Low temperatures, on the other hand, may have the opposite effect, and either augment weak fluorescence or cause it to occur in normally non-fluorescent specimens (8). The term "cryoluminescence" has been coined by the writer to describe this phenomenon.

For more detailed information on the theory of luminescent phenomena, reference should be made to texts by Garlick (5), Mott and Gurney (11), or Pringsheim (12).

The majority of trace elements will serve as activators of one kind or another in mineral phosphors. Such elements may roughly be divided into



A. DISTRIBUTION OF RADIOACTIVITY ADJACENT TO CONTACTS. (AFTER GROSS, 1952; DANIALS & SAUNDERS, 1951)

B. BOURLAMAQUE BATHOLITH, QUEBEC. (AFTER INGHAM & KEEVIL, 1951)

C. DOME STOCK, RED LAKE, ONT. (AFTER GROSS, 1952)

FIG. 1

those that combine with other elements to form the less common minerals, and those that rarely or never form minerals but are generally held in the crystal lattices of the rock-forming minerals. The former commonly occur as the stoichiometric excess type of phosphor, whereas the latter may be either a diadochoic replacement, or occupy an interstitial position in the phosphor lattice.

The spatial arrangement of trace elements in rocks has been studied extensively in recent years by means of spectrochemical and chemical surveys. A very large proportion of these studies have been made in the vicinity of ore

deposits, and, although no general rule can be laid down, some type of zoning is commonly present. This zoning may occur as diagnostic suites of minerals or trace elements in or near specific geologic units, and may be of two general types, which are (a) concentrated within certain rock types; or (b) independent of the rock type, and varying more or less uniformly in concentration or kind with increasing distance from the center of the ore body. In this same connection, small but detectable amounts of radioactivity occur in almost all rocks, and its distribution in batholiths and associated hydrothermal ore deposits has been the subject of several recent studies (6, 7). These studies have shown that the low radioactivity of batholithic rocks is commonly concentrated in certain parts of the intrusive masses. Radioactive highs of this type are often found to occur close to hydrothermal ore deposits within the batholith margin, or the nearby country rock. The highest radioactive values are generally in or very near the ore zones (6). Typical examples of the relationship of radioactivity to small batholithic bodies and ore deposits are illustrated in Figures 1B and 1C. The distribution of radioactivity adjacent to the contacts of certain ore deposits is shown in Figure 1A. In this diagram, Curve A is the distribution of radioactivity adjacent to ore deposits in basic rocks, with the peak radioactivity located five to twenty feet from the ore contact (6); Curve B is the distribution of radioactivity adjacent to ore deposits in acidic intrusive rocks (6); and Curve C is the distribution of radioactivity adjacent to a small basic igneous stringer in granitic rocks (3). It is tentatively suggested that the radioactive high adjacent to certain ore bodies and intrusives may be termed a "radioactive front," and may be analogous to the "basic front" of metamorphic granites.

THE GEOLOGY AND DISTRIBUTION OF LUMINESCENCE IN SEVERAL AREAS

The distribution of luminescence in and near intrusive rocks and ore bodies was investigated using several types of luminescent phenomena all of which were developed using simple methods. These were: fluorescence excited by both long and short ultraviolet radiations; cryoluminescence produced by ultraviolet radiations on specimens that had been chilled on dry ice to about − 50° C; and thermoluminescence produced by heating specimens below a red heat (about 200–300° C) on a hot plate. In all cases, the observations were made in a dark room, with precautions being taken when testing for thermoluminescence to eliminate any light from the coils of the hot plate. The last mentioned type of luminescence is strongly dependent upon lattice imperfections due to radioactivity, whereas the others are more closely related to trace elements in the crystal lattice.

The fluorescence that was noted in the walls of underground workings and in hand specimens from the Perron and Bevcourt mines, occurred in masses of minerals that generally were an inch or more in diameter, with some smaller fluorescent specks. In the majority of cases where cryoluminescence or thermoluminescence was observed in hand specimens, the former usually appeared as tiny specks, colored pink, white or yellow, about two or three millimeters across, and the latter as a whitish glow over the entire surface of the specimen.

Investigations were carried out on rocks from six areas, brief descriptions of which follow below. With one exception, they are located in the mining district of northwestern Quebec, about 300 miles northwest of Montreal.

Pascalis Township.—The area examined comprises the southern half of this township, which lies about 15 miles northeast of the town of Val d'Or. The rocks are all of Precambrian age, and consist of altered Keewatin-type lavas and pyroclastics, small sills of peridotite and diorite, numerous small basic and acidic dikes, parts of the post-Keewatin Bourlamque and Pascalis-Tiblemont batholiths, and a Keweenawan-type diabase dike. The Bourlamaque batholith is the better known of the two larger intrusives, and is composed of rocks called variously "granodiorite" and "quartz gabbro with an albite tonalite marginal phase." Numerous small dikes of basic to acidic composition cut the main mass. The radioactivity of this batholith has been found to be concentrated around the margins (Fig. 1B). In Pascalis township there is a chlorite-amphibole alteration zone in the lavas, extending for about a mile to the east of the batholith-extrusive contact. The Perron mine, which is described below, is one of several mines located around the eastern, southern and western edges of the batholith.

The portion of the Pascalis-Tiblemont batholith within the area being considered consists of albitic granite, granodiorite, and quartz diorite, with some areas of syenite, monzonite and gabbro. Silicification of the adjoining lavas and pyroclastics, believed to be due to the intrusion of this batholith, has been observed along the western contact, but is only present in a few small areas along the southern contact. This silicified zone is marked by the development of much biotite in the altered extrusives. No ore deposits are known to be associated with the portion of the batholith which is presently under consideration, although a small zone of pyrite-marcasite mineralization in acidic tuffs has been observed at the southern end of Lac Tiblemont.

The lavas, pyroclastics and minor intrusives lying between the batholiths and their associated zones of alteration are characteristic of similar rocks in this portion of the Canadian Shield. Low grade metamorphism has destroyed or obscured the original minerals, but such features as pillows, bedding, and vesicules are still present (9, 10).

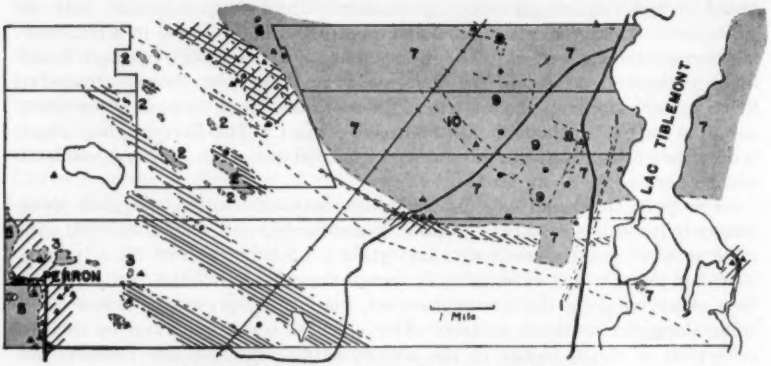
About 170 specimens of rock from the area were examined for thermoluminescence, fluorescence, and cryoluminescence. The distribution of the luminescent specimens is shown in Figure 2.

Fluorescent and cryoluminescent specimens are concentrated in the Bourlamaque batholith margin. Both phenomena are closely associated with the presence of carbonate present in visible or microscopic amounts in the specimens. Manganese probably serves as an activator in the carbonate minerals (see Perron Mine). The thermoluminescence which was observed in specimens from the batholith margin has been doubtfully correlated with the presence of chlorite. Luminescence of all three types may occur in any of the rock types found in the batholith, and luminescent and non-luminescent specimens have been found within a few feet of each other. Examples of multiple luminescence, in which more than one type of luminescence were noted in the same specimen, appear to be restricted to the vicinity of the Perron Mine. The

luminescent intensity of specimens from this mine was the highest of any noted in the rocks from Pascalis Township.

In the chlorite-amphibole alteration zone adjoining the Bourlamaque batholith, the occurrence of thermoluminescence in specimens can be definitely related to the presence of chlorite in the rocks. If the alteration is restricted to amphibolitization, the rocks are non-luminescent.

Thermoluminescence was observed in epidotized rocks immediately west of the silicified zone adjoining the Pascalis-Tiblemont batholith, and may be connected with the presence of the epidote. Thermoluminescence also occurs in



SOUTHERN HALF OF PASCALIS TOWNSHIP

MINOR INTRUSIVES-
1. DIABASE, 2. DIORITE, 3. PERIDOTITE.
MAJOR INTRUSIVES-
BOURLAMAQUE BATHOLITH- 5. GRANODIORITE.
PASCALIS-TIBLEMONT BATHOLITH- 6. GRANITE, 7. GRANITE, GRANODIORITE AND QUARTZ DIORITE, 8. SYENITE, 9. MONZONITE, 10. GABBRO
PYROCLASTICS-
TUFF, AGGLOMERATE, MINOR GREYWACKE AND LAVA.
LAVAS-
ANDESITE, TRACHITE, DACITE.
ALTERATION ZONES.
MASSIVE SULPHIDES.
▲ THERMOLUMINESCENCE. • FLUORESCENCE OR CRYOLUMINESCENCE.

FIG. 2

several places within the silicified zone and close to the batholith contact with the same phenomenon noted in specimens from the small silicified area in the southeastern part of the map. Cryoluminescence was noted in a few places within and near the contact between the silicified zone and the less altered extrusives.

Within the Pascalis-Tiblemont batholith, there appears to be a narrow luminescent zone extending in for about one-quarter of a mile from the contact. It may be significant that this approximately coincides with numerous inclu-

sions of lavas and pyroclastics in the intrusive rocks. Elsewhere, the luminescence is principally cryoluminescence, and has a rather erratic distribution. This may be due in part to insufficient specimens to outline luminescent highs. The cryoluminescence of the granite and granodiorite is known to be due to microscopically small amounts of microcline (8).

Scattered luminescence occurs in the lavas, pyroclastics and minor intrusives lying between the alteration zones of the two batholiths, and consists principally of cryoluminescence and fluorescence. This is probably related to grains of carbonate in the pyroclastics, but the luminescent mineral in other rock types is unknown. No luminescent phenomena were observed in association with the diabase dike or the pyrite-marcasite zone that is located south of Lac Tiblemont.

Perron Mine.—This mine is located in the southwestern corner of Pascalis Township. Approximately $15,500,000 worth of gold was produced from the property between 1935 and 1951, when ore reserves were exhausted. The gold occurs in a series of steeply dipping quartz veins just within the contact of the Bourlamaque batholith and the extrusives. Other vein minerals in their approximate order of frequency of occurrence are: black tourmaline, pyrite, ankerite, calcite (some of which exhibits a pink fluorescence), chalcopyrite, blue white fluorescent scheelite and fuchsite. The principal structural controls for the localization of the veins are the east-west Perron shear and a lava roof pendant.

Spectrochemical analyses have shown, in the veins of the ore zone, Cr > Ti and Cr > Mn (1) whereas in the quartz veins outside of the ore zone Ti > Mn > Cr,[3] and in the fluorescent calcites which occur only outside the ore zone Mn > Ti > Cr.[3] Most of the scheelite is found at the outer limits of the ore and the fluorescent calcite in all cases is outside of both the ore zone and the scheelite zone. The gold ore thus appears to be enveloped by two zones of fluorescent minerals that roughly correspond to an apparent zoning of the trace elements. In this connection, it is of interest to note that the sparse occurrence of fuchsite may form a third zone inside the scheelite zone. The nonluminosity of calcite that is found within the ore zone is probably partly due to poisoning by iron, and partly to lack of manganese as an activator.

Bevcourt Mine.—This mine is in Louvicourt Township, about 20 miles east of Val d'Or. It is situated in the northern edge of a plug of granodiorite, which is markedly similar to the rocks of the Bourlamaque batholith. Gold is presently being mined from quartz-vein stockworks and a series of large, flat-dipping quartz veins. The minerals of the quartz veins include black tourmaline, pyrite, chlorite, ankerite, calcite (occasionally exhibiting a pink fluorescence), scheelite, sphalerite, and rare occurrences of fluorite. The ore zone is bounded on the south by a feldspar porphyry dike intruded into the granodiorite, and on the north by the granodiorite-lava contact. There is some suggestion that the ore zone is raking gently to the east.

Scheelite occurs principally at or near the assumed eastern and western limits of the ore zone, but the distribution of the fluorescent calcite does not follow any discernible rule.

[3] Spectrochemical analyses made by the Quebec Dept. of Mines Laboratories.

Canadian Malartic Mine.—This mine is in Fourniere Township, about 20 miles west of Val d'Or and near the town of Malartic. The ore bodies consist of silicified Precambrian feldspar porphyry masses and Temiscamingue-type greywacke, both mineralized with pyrite, which carries gold and silver (4).

Ten specimens of diamond drill core from this mine, which were supplied by Dr. P. R. Eakins, were tested for fluorescence, cryoluminescence and thermoluminescence. Cryoluminescence from an unknown mineral was observed in specimens from just inside one of the porphyry ore zones. Strong thermoluminescence in altered porphyry was found to extend out from the ore-contact for a distance of about eight feet. No examples of fluorescence were noted.

Normetal Mine.—This mine is located in Desmeloizes Township about 50 miles north of Noranda, in the western part of the northwestern Quebec mining district. Precambrian tuffs and lavas, cut by several intrusive rocks, are found in the immediate vicinity of the mine. The ore consists of massive sulphides containing Cu, Zn, Au, and Ag, which have replaced a band of rhyolitic agglomerate. Intrusive "rhyolite" and a diabase dike are found in the ore zone (2).

Eighteen specimens of diamond drill core from the ore zone and adjacent tuffs, which were supplied by Dr. J. E. Riddell, were tested for fluorescence and thermoluminescence. No thermoluminescence was observed in the altered tuffs until the ore zone contacts were reached, when specimens from close to both the hanging wall and foot wall luminesced. Luminescence was not observed to occur in the massive sulphides, but a specimen of unreplaced agglomeritic tuff from the ore zone showed strong luminescence in the larger fragments. Fluorescence was not observed in any specimens examined.

Birch Lake, Manitoba.—Several specimens of diamond drill core from Birch Lake near Flin Flon, Manitoba, were supplied by Mr. J. F. Macdougall. These specimens consisted of chloritic schist from near the contact of a small chalcopyrite body and sheared agglomerate and tuff, which has been progressively replaced by magnetite and pyrite. Tests were made for thermoluminescence and fluorescence, all of which were negative.

CONCLUSIONS

1. Luminescent phenomena may occur in a marginal position to certain intrusive masses and hydrothermal ore bodies. The lack of luminescence adjacent to other intrusives and sulphide deposits may be due to: i) lack of suitable activators; ii) "poisoning"; or iii) poor distribution of specimens.

2. Fluorescent and cryoluminescent minerals are generally due to trace element "activators" or stoichiometric excesses of ions. The trace elements that either activate pre-existing minerals or form new minerals appear to have been introduced during the emplacement of magmas or the introduction of mineralizing solutions. In special cases, mineral phosphors formed in this manner may serve to outline ore bodies or intrusives, but in general such phosphors appear to have a rather erratic distribution.

3. Thermoluminescence is principally due to the effect of radioactivity on the crystal lattices of minerals. The occasional relationship of the phenomena

to platy minerals, such as chlorite, and possibly biotite, may indicate that the sheetlike structure of the crystal lattice provides suitable conditions to hold radioactive elements or ions in interstitial positions.

4. Thermoluminescence can probably be employed to differentiate between zones of high and low radioactivity in intrusive rocks, and thus be of value in locating potential ore zones. In the altered country rock close to such intrusives, the phenomenon is probably closely related to radioactivity that was introduced during the emplacement of the intrusive.

5. In both intrusive and extrusive basic rocks that are host to massive sulphide deposits and vein deposits, there appears to be a narrow zone of radioactivity that has been concentrated as a sort of "radioactive front" just outside the limits of the ore. Similar "fronts" also appear to be present adjacent to ore bodies in acidic extrusives. In the case of ore bodies in acidic intrusives, the "front" may be masked by the radioactivity of the igneous body. It is suggested that the thermoluminescence that is connected with this "front" offers a simple means of determining the limits of some ore bodies. In conjunction with diamond drilling it may be of particular value in determining the proximity of ore. There is some suggestion that the width of the "front" varies directly with the size of the ore zone.

6. The conclusions stated above are based on data of a very preliminary nature, and further research is required.

ACKNOWLEDGMENTS

The foregoing embodies the principal features of research done largely at McGill University towards the requirements for the degree of doctor of philosophy. The field work was carried out under the auspices of the Quebec Department of Mines, which also supplied funds and equipment to carry out part of the experimental work.

The help of the staffs of the Perron and Bevcourt Mines, several branches of the Quebec Department of Mines, and the Department of Geology at McGill University is gratefully acknowledged. The writer is particularly grateful for the help and criticism of Dr. J. S. Stevenson of McGill University.

Addenda:

After the foregoing was written, an additional test was made of the distribution of thermoluminescence adjacent to the ore bodies of the East Sullivan mine, located in Bourlamaque township about four miles southeast of Val d'Or. Here, three large sulphide replacement bodies (and a number of smaller ones) occur in silicified and chloritized rhyolitic volcanics and contain economic amounts of copper, zinc, gold and silver. A number of diorite dikes have been found in the ore zone and syenite porphyry and diorite porphyry masses terminate the favorable zone to the east and west. Andesitic flows, which are not favorable for replacement, provide the north and south boundaries of the altered rhyolitic rocks.

Five diamond drill holes, each of which passes completely through one or more of the ore bodies, were selected for the test. Ninety-eight specimens,

averaging about two inches in length and spaced not more than twenty-five feet and not less than five feet of core length apart, were heated and observations made for the occurrence of thermoluminescence. In general, the specimens in which luminescence occurred came from zones extending out from the contacts of the ore bodies for distances of up to forty feet, although it was less in most cases and lacking at four out of the fourteen contacts intersected by the five drill holes. A few specimens from within the ore bodies also showed luminescence, which appeared to be connected with areas of incomplete replacement.

The interest and assistance of Mr. C. P. Robertson, geologist at East Sullivan, is gratefully acknowledged.

44 HOPEDALE AVE.,
TORONTO, ONTARIO
March 30, 1954

REFERENCES

1. Auger, P. E., 1941, Zoning and district variations in the minor elements in pyrite of Canadian gold deposits: ECON. GEOL., vol. 36, p. 401–423.
2. Brown, W. L., 1948, Nonmetal Mine, Structural Geology of Canadian ore deposits: Canadian Inst. of Min. and Metallurgy, p. 683–692.
3. Daniels, F. and Saunders, D. F., 1951, The thermoluminescence of crystals: Final Report U.S.A.E.C. Contract AT(11-1)-27 (mimeographed).
4. Derry D. R., and Hertz, H. C., 1948, Canadian Malartic Mine Structural Geology of Canadian ore deposits: Canadian Inst. of Min. and Metallurgy, p. 853–857.
5. Garlick, G. F. J., 1949, Luminescent Materials, Clarendon Press, New York.
6. Gross, W. H., 1952, Radioactivity as a guide to ore: ECON. GEOL., vol. 47, p. 722–742.
7. Ingham, W. N., and Keevil, N. B., 1951, Radioactivity of the Bourlamaque, Elziver and Cheddar Batholiths, Canada: Bull. Geol. Soc. of Am., vol. 62, p. 131–158.
8. McDougall, D. J., 1952, Some factors influencing fluorescence in minerals: Am. Mineralogist, vol. 37, p. 427–437.
9. McDougall, D. J., 1951, Preliminary report on the southwestern part of Pascalis Township, Abitibi-East County: Quebec Dept. of Mines Prelim. Rept. 258.
10. McDougall, D. J., Preliminary report on the geology of southeast Pascalis and part of southwest Tiblemont Townships, Abitibi-East County: Quebec Dept. of Mines Prelim. Rept. (in preparation for publication).
    The geology of southern Pascalis Township and part of Tiblmeont Township, Abitibi-East County, Quebec: Quebec Dept. of Mines Geol. Rept. (in preparation for publication).
11. Mott, N. F., and Gurney, R. W., 1940, Electronic Processes in Ionic Crystals, Clarendon Press, New York.
12. Pringsheim, P., 1943, Luminescence of Liquids and Solids, Interscience Publishers, New York.

NATURE OF THE ORE-FORMING FLUIDS AT VARIOUS STAGES—A SUGGESTED APPROACH[1]

EARL INGERSON

WHEN I received an invitation to contribute to a discussion on the derivation, nature, and transfer of the ore-forming fluids, it was suggested that attention be confined to such fluids *prior* to the time of crystallization of the ore minerals. My first reaction was very much like the one expressed by F. Gordon Smith in his contribution to the discussion, that if we know so little about the nature of the ore-forming solution at the time it deposited the minerals, what chance do we have of even discussing the nature of those fluids before deposition began? However, as I thought about it more and more, it occurred to me that ideas and techniques are available that might make it possible to develop means of interpretation that could shed some light on this problem in the near future.

The nature of the solutions that give rise to ore deposits has been discussed many times in recent years. Some of these discussions have been theoretical—what kind of fluid would be expected from a crystallizing magma? Others have centered around studies of the ore deposits and their surroundings—kind(s) of alteration produced, mineral assemblages deposited, or nature of the residual solution in liquid inclusions of the ore minerals. Both approaches have attempted to characterize the solutions according to (1) composition, (2) temperature, (3) state and density (which involves pressure), (4) pH, (5) amount. Both have been concerned with the nature of the fluids at the time the ore minerals were formed. Partly for this reason the discussions have generally failed to recognize that the whole setup is a dynamic system and that the solutions are changing in character significantly both with space and with time. The solution first expelled from a crystallizing magma may bear only slight resemblance to the final fraction. After a solution has traversed several thousand feet of country rock it will almost certainly be quite different in composition, temperature, pH, and other properties, than when it left the crystallizing magma.

Realization of these changes in composition and other properties obviates some of the difficulties inherent in trying to explain the deposition of ore minerals, quartz, and other minerals from solutions of the composition of those now found in liquid inclusions merely by decreased solubility brought about by lowering the temperature. Explanation of known ore deposits, quartz veins, and similar occurrences on this basis would require many times as much water as could possibly have been available. The solutions as we find them are the final spent fractions; when they left the magma they may have contained vastly more heavy metals, silica, and other constituents that have been deposited than

[1] Publication authorized by the Director, U. S. Geological Survey. Presented before the Society of Economic Geologists, Los Angeles Meeting, February 1953.

they do now. And not just the saturation value at elevated temperature of the compounds deposited; elements concerned may have been present as soluble compounds and the precipitation may have been by reaction rather than by simple decrease in solubility of compounds in the solutions.

Reaction could come about in a number of different ways; e.g., (1) neutralization of acidic solutions by reaction with limestone country rock; (2) reaction with contained water (solutions) of sedimentary rocks; (3) reaction with ground water; (4) reaction with other ascending solutions (a) derived from another intrusion or (b) derived from the same intrusion at a different time.

Most of these types of reactions are readily visualized, but perhaps (4b) requires some explanation. Suppose, for example, that the more volatile components, such as water, hydrogen sulfide, and carbon dioxide are expelled differentially early in the sequence of crystallization. They ascend from the magma chamber and as they condense and stop up the pores there is a slowing down at a definite position above the magma chamber. Later on, when most of those components have been expelled, lead, for example, comes off, not as lead sulfide but as a soluble compound of lead being carried out in a water solution, perhaps in considerable concentration. As this solution catches up with the hydrogen sulfide-bearing components reaction takes place and lead sulfide is deposited. If that mechanism works, then a relatively very small amount of water can carry the entire amount of lead sulfide not as the sulfide but perhaps as separate solutions of hydrogen sulfide and lead chloride.

The same thing might work with silica—with early expulsion of water and carbon dioxide, and instead of having silica dissolved and taken out of the magma as such, a soluble silicate might be extracted later. There is ample evidence from liquid inclusions in quartz that the solutions are high in alkalis, particularly in soda. Suppose there is in effect a solution of sodium disilicate or a sodium silicate that contains 70 to 72 percent silica. This can exist in a fairly concentrated solution and still maintain its fluidity and mobility. If such a solution comes into a region high in carbon dioxide, reaction takes place, quartz becomes the stable phase, and much quartz can be deposited from a relatively small quantity of water.

The above discussion and the new approach I am suggesting involve an assumption as to the origin of the solutions. If we are studying solutions at the time of deposition of the minerals it makes little difference where these solutions came from—important but still not essential for some types of discussion. But if we are going further back in time, as has been suggested, it is necessary to assume something as to the origin of the solutions. The remarks that I have to make, therefore, are directed at situations where there is a fair amount of evidence that the solutions have been derived by the crystallization of an igneous magma. The title of the paper suggests that we look at these ore-forming solutions at various stages. We could pick out an indefinite number of stages and substages for discussion, but for purposes of simplification I propose to discuss specifically three stages—(1) the original dissolved water in the magma, (2) the solution in the interstices and liquid inclusions

of the igneous minerals themselves, and (3) the liquid inclusions in the ore-forming and related minerals.

Now, how can we possibly tell anything about the nature of the original water content of the magma when we do not even know how to determine the amount of water originally present? I remember about five yeas ago at Steamboat Springs, Nevada, Don White and I were discussing the possibility of estimating the amount of juvenile water in hot springs, geysers, and eventually in ore-forming solutions. We came up with the idea at that time that it might be possible to get from deep-seated igneous rocks, for example, at the bottom of Yosemite Valley, hydrous minerals that crystallized directly from a melt, drive off the water, and determine its isotopic composition. That is about all that could be determined from water of hydration in minerals because it certainly has no dissolved solids in it. If we can start there and determine the isotopic composition of the hydrogen and oxygen of the water, that gives us at least one property that we might tie to and relate to properties of the solutions at later stages. Probably at the temperature of crystallization there would be little or no isotopic fractionation, either by fractional crystallization or by diffusion, so we might take that as a first approximation of the isotopic composition of the original water.

If it should be demonstrated that isotopic fractionation does take place under these conditions, then a much more complex series of determinations would be necessary to estimate the isotopic composition of the original water of the magma. The following things would have to be determined, or estimated:

(1) Amount of water in the original magma.

(2) Total amount and isotopic composition of the water remaining in the igneous rock as:

(a) Water of hydration in the hydrous minerals.

(b) Solutions in liquid inclusions and in the intergranular.

(3) Amount and isotopic composition of the water expelled during crysallization:

(a) Solutions in associated ore deposits, quartz veins, or contact zones.

(b) Solutions that have gone on through to the surface, or have escaped into the country rock in such a manner that their water can no longer be related to the intrusion.

Of these quantities only (2) can be determined with fair assurance of accuracy. (3a) could be estimated under favorable circumstances. Estimates of the amount of water of (3b) would be subject to a great deal of interpretation, but its isotopic composition might be approached as follows: If there is a progressive change in the isotopic ratios of H_2 and O_2, say a decrease [2] in the proportion of the heavy isotopes from water of hydration through liquid in-

[2] This is the direction of fractionation that would be expected theoretically, but several independent experiments (Erlenmeyer and Gärtner (2)[3]; Emeleus *et al.* (1); Verdnasky, Vinogradov, and Teis (6)) suggest that hydrous minerals take up and hold the *lighter* molecules preferentially. However, no bona fide igneous minerals have yet been studied in this manner.

[3] Numbers in parentheses refer to References at end of paper.

clusions in the igneous rock to liquid inclusions of ore minerals, then water that has moved out still farther may logically be assumed to contain a still higher proportion of the lighter isotopes. By extrapolation, therefore, a value for isotopic composition of this water might be obtained.

Estimates of the amount of water that has escaped would be little more than guesses, but the guesses can be controlled by remembering that this amount of water, plus that in deposits around the intrusion, plus what remains in the igneous rock must equal the original water content of the magma. The present concensus is that granitic magmas do not contain more than about 4 percent of water.

The weighted average, then, of the isotopic composition of these various fractions of water would be that of the original water in the magma.

For the next stage, the formation of liquid inclusions in late minerals and incorporation of the residual aqueous solution in the intergranular, the isotopic composition should also be determined. Very likely by the time the final fraction of the magma has crystallized the water remaining in the interstices and in the liquid inclusions will have undergone at least a certain amount of isotopic fractionation. Urey and Greiff and others have calculated that reactions involving deuterium and hydrogen will show a value of the equilibrium constant significantly different from unity at temperatures up to 500° or 600° C, and it is entirely possible that the final fractions of a magma may not crystallize until comparable temperatures have been reached. In addition to the isotopic composition there should be determined, of course, the material dissolved in this interstitial solution and in the liquid inclusions. If possible the small mineral crystals in the liquid inclusions and the solubility of the host mineral in the fluid of the inclusions should be determined, which would give as good an estimate as can be obtained of the composition of the ore-forming fluid at this intermediate stage. These determinations should be made not only for intrusions that have related ore deposits but also for those of comparable over-all composition that have no known ore deposits related to them. These determinations could be highly significant, as is pointed out below in the discussion of reconnaissance exploration work.

The same types of determinations then should be made for the liquid inclusions in ore minerals in veins and in the related gangue minerals. Amount of water, isotopic composition, and minor element content should be determined in the solutions from both types of minerals. Those determinations will be of general theoretical interest. Certainly any information we can get that has not been available before will be interesting to all geologists, especially those concerned with ore deposits. But is there any practical application that we can make of that information once we get it? I should like to suggest that there may be; that in the near future it might be possible to use such determinations as a powerful tool in suggesting where to look for additional ore deposits. If these isotopic compositions show significant variations then they should be plotted on a diagram or a series of diagrams; the hydrogen/deuterium ratio, the O^{16}/O^{18} ratio against anything to which they might be related—against temperature, stage of crystallization and differentiation, distance from the center or from the periphery of the intrusion, etc.

If the isotopic composition is the same in a granodiorite that has no known ore deposit related to it as in one that has abundant ore deposits, these same functions (temperature, stage, distance) might be plotted against the minor element content of the liquid inclusions of the igneous rock and against those of the related ore deposits. Is there any systematic change, any trend that we can detect? Is there a systematic difference between barren and ore-related intrusions? If there is, that gives us a new tool right away; if a significant relationship can be demonstrated, then it may be possible to go to a part of a large batholith which is known to have associated ore deposits in other places, collect a sample of the water, make an isotopic determination or a minor element determination and suggest whether or not there should be ore deposits related to that part of the intrusion. Or, go one step further back: Go into an area that has not been explored at all and study an igneous intrusion in the same manner. We may be able to get a clue as to whether it is worth while to do any detailed and systematic exploration work. We may be able to say immediately from some of these determinations that there is little or no possibility that ore deposits are related to this particular intrusion.

These studies of water and minor element content can be pursued a little farther and perhaps approached from a slightly different point of view. It has been taken for granted fairly generally, just intuitively, that an intrusion which has given rise to copper deposits or to zinc deposits should contain more copper or more zinc, respectively, than a barren intrusion that does not produce such ore deposits. This concept can be approached from a diametrically opposed viewpoint. Is it not possible that an intrusion may be low in the element that has come out of it and concentrated in an ore deposit because it has been swept out by the water during crystallization and deposited outside of the intrusion?

Situations have been described in the literature which indicate that such may be the case. For example, Mackin (3) finds that the iron deposits of the Iron Springs district, Utah, are formed by what he calls "deuteric differentiation." That is, at a late stage in crystallization of the quartz monzonite magma part of the iron was extracted from the mafic minerals by deuteric alteration and deposited, principally as magnetite, in the near-by joints. Thus, the part of the igneous rock immediately associated with the iron ores is *low* in iron. The peripheral shell, on the other hand, crystallized relatively rapidly and had no opportunity for deuteric differentiation. This part of the intrusion has barren joints and is *higher* in iron than those parts that contain the deposits of iron ore.

Phair (4) has studied the uranium-bearing bostonites of the Central City district, Colorado, where the ore minerals are not concentrated in the igneous rocks, but in the related veins. The same type of relationship, however, as that described above for the Iron Springs district is observed in this area; the uranium-bearing veins are associated with bostonites or parts of bostonites that are *low* in uranium. The uranium has been taken out of the dike and deposited in the vein.[4]

[4] It has long been realized that elements added to a contact zone by a magma are likely to be low in the solidified intrusive rock. For example, Lacroix (Étude minéralogique de la lherzolite des Pyrénées et de ses phénomènes de contact, Arch. Mus. Hist. Nat. Paris (3), Vol.

This relationship may also be true of larger bodies of igneous rock. In a stock or even in a batholith, is it not possible that the element in which we are interested has been taken out of the intrusion? If that is the case, then perhaps a barren intrusion will be higher in copper or lead or zinc than the intrusion that has deposits of those elements around it. One example of a place where this hypothesis might be tested is the Silver City, New Mexico, district where there are two similar intrusives, one barren and the other with associated ore deposits.

The same thing might be done for water content, apart from isotopic composition, which I have already suggested should be plotted against such things as temperature, stage, or distance. The amount of water might work exactly the same way. We are inclined to think that an intrusion that is high in water is the one that should have produced the ore deposits. Might that not also work the other way? It may be that an intrusion low in water now is low because the conditions of crystallization were such that most of the water was expelled and carried the metals out and deposited them outside of the intrusion. For example, a highly serpentinized intrusion may contain some 10 percent of water, show no contact effects, and have no related ore deposits, whereas a granitic intrusion that now contains only a fraction of a percent of water may have extensive contact effects and related hydrothermal deposits. Thus, it might be that the barren intrusions are the ones that are high in water and the ore-related ones low in water.

Studies such as those suggested are feasible at the present time. Instrumentation and techniques to carry them forward are available in several places. With more and more mass spectrometers being built, it would be a comparatively simple matter to make collections of water at these various stages, determine the isotopic composition, and at the same time take the residues and

---

6, p. 209–308, 1894) points out (p. 298–300) that the contact rocks around a lherzolite intrusion are rich in alkalies and B_2O_3. He says that these elements must have come from the intrusive rock, although the lherzolite is *low* in them.

Larsen (A hydrothermal origin of corundum and albitite bodies, ECON. GEOL., vol. 23, p. 398–433, 1928) observes that a common type of contact metamorphism by peridotite is the development of schists that are rich in albite and sodium-bearing mica and amphiboles. He generalizes this point of view: "Magmas commonly give rise to contact metamorphic zones composed of constituents in which they are low" (p. 432).

Lodochnikov (Serpentine und Serpentinite der Iltscherlagerstatte und in allgemeinen und damit verbundene petrologische Probleme, Trans. Cent. Geol. & Prosp. Inst., Fasc. 38, 817 pp., 1936; German Summary 728–770) cites these and many more examples, some with and some without literature references. Lodochnekov formulates the concept into what he calls the "polarity rule" for magmatic and post magmatic minerals from one and the same magma (p. 743): "The post-vulcanic processes bring elements (out) in which the rock which conditioned the processes, is *low*."

It should be realized that this rule does not always work; in a given situation its applicability is determined not only by concentrations of the elements concerned, but also by the relation of the ionic radii and charges and other properties of the elements that might be swept out of the magma and the same properties of the elements entering into the minerals crystallizing from the magma. In one situation a given minor element might be concentrated in the residual solutions and swept out of a magma almost quantitatively, whereas in another set-up the same element might proxy for a more abundant one in minerals crystallizing from the magma and thus remain largely in the intrusive rock.

The applicability of the polarity rule to veins and other types of deposits farther removed from the generating igneous rock than the contact deposits mentioned above should be thoroughly investigated.

determine the minor element content. It is possible that some important conclusions concerning the nature of the ore-forming fluids prior to the time of deposition might emerge from these studies. If so, this information would also supplement current knowledge of the nature of the ore-forming fluids at the time of deposition of the ore minerals. There should be no marked discontinuity between the nature of the fluids before and during deposition. If there proves to be a systematic relationship between the isotopic composition of water in primary hydrous igneous minerals of an intrusion, the water contained in late liquid inclusions and the intergranular spaces of the rock, and in associated ore deposits, the case for derivation of the ore-forming solutions from the magma by crystallization will be greatly strengthened.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
March 18, 1954

REFERENCES

1. Emeléus, H. J., James, F. W., King, A., Pearson, T. G., Purcell, R. H., and Briscoe, H. V. A., 1934, The isotope ratio in hydrogen; a general survey by precise comparisons upon water from various sources: Jour. Chem. Soc., London, p. 1207–1209 and 1948–1950. Discussion by H. V. A. Briscoe, Chemistry and Industry, vol. 53, p. 491–492, June 1, 1934.
2. Erlenmeyer, H., and Gärtner, H., 1934, Some experiments on heavy water: Nature, vol. 134, p. 327.
3. Mackin, J. Hoover, 1947, Some structural features of the intrusions in the Iron Springs district: Guidebook to the Geology of Utah, no. 2, 62 p.
4. Phair, George, 1952, Radioactive Tertiary porphyries in the Central City district, Colorado, and their bearing upon pitchblende, deposition: U. S. Geol. Survey Trace Elements Inv. Rept. 247, 53 p. (open filed by the U. S. Atomic Energy Commission, Technical Information Service, Oak Ridge, Tennessee).
5. Urey, Harold, and Greiff, Lotti J., 1935, Isotopic exchange equilibria: Am. Chem. Soc., Jour., vol. 57, p. 321–327.
6. Vernadsky, V. I., Vinogradov, A. P., and Teis, R. V., 1941, Determination of the isotopic composition of waters in metamorphic rocks and minerals: Akad. Nauk. SSSR, Doklady, vol. 31, p. 573–576.

THE FORMATION OF INTERMEDIATE SULFIDE PHASES IN THE SOLID STATE

VIRGINIA ROSS

CONTENTS

PAGE

Abstract 734
Solid state reactions involving the formation of ternary sulfides from the corresponding binary sulfides 734
System: Cu_2S-CuS 734
System: Cu-Fe-S 737
Systems: Cu_2S-Sb_2S_3, Cu_2S-Bi_2S_3, PbS-Sb_2S_3, PbS-Bi_2S_3, Ag_2S-Sb_2S_3, Ag_2S-Bi_2S_3 and Sb_2S_3-Bi_2S_3 737
Recent solid-state investigation at low temperatures of the systems: Cu_2S-Sb_2S_3, Cu_2S-As_2S_3, Cu_2S-FeS and Cu_2S-CuS 738
Comparison of the chalcocite and digenite phases 739
The mechanism of formation of the intermediate sulfide phases 740
Determination of the relative rates of formation of the intermediate phases 744
Discussion of experimental results 745
Conclusions 747
Relation to "un-mixing" and "ex-solution" phenomena 749
Geological significance 749
References 751

ABSTRACT

A theory of formation of intermediate sulfide phases in the solid state is proposed to explain the phenomena observed in studying the phase equilibria of such systems as: Cu_2S-CuS, Cu_2S-Sb_2S_3, Cu_2S-As_2S_3, and Cu_2S-FeS. The theory of formation (and the reverse process of "ex-solution") is based upon the simultaneous and chemically-equivalent interchange of two different kinds of metal ions, which migrate in opposite directions through the relatively stable sulfur network of a developing ("ex-solving") intermediate phase.

The rates of intermediate phase formation in the systems studied were observed to be very rapid and to obey Tammann's parabolic rate rule for diffusion. The diffusion process is apparently dependent on the prevailing interstitial disorder of the copper atoms of chalcocite. The role of solid-state diffusion is stressed with regard to the formation of sulfosalt and complex sulfide minerals in ore bodies located at moderate to greater depths, as well as those that undergo thermal metamorphism.

SOLID STATE REACTIONS INVOLVING THE FORMATION OF TERNARY SULFIDES FROM THE CORRESPONDING BINARY SULFIDES

System: Cu_2S-CuS.—The first inclusive study of the system Cu_2S-CuS was carried out in 1915 by E. Posnjak, E. T. Allen and H. E. Merwin (19),[1] who indicated that there was a limited field of solid solution between chal-

[1] Numbers in parentheses refer to References at end of paper.

cocite and covellite. The inversion temperatures were obtained for solid solutions of Cu_2S and CuS using compacted mixtures of chalcocite and covellite, which had been previously annealed at 110° C. The temperature of inversion of pure chalcocite was recorded at 91.1° C. Solid solutions containing 3% CuS inverted at 93.1° C; 5% CuS at 93.4° C; and 6% CuS at 93.6° C. For solid solutions containing greater than 8% CuS no heat effect was observed. The disappearance of the heat effect was unexplained.

Alan M. Bateman and Samuel G. Lasky (1) in 1932, using natural crystals of chalcocite and covellite, discovered that within the temperature range from 75° to 150° C, as much as 30 to 40 percent covellite dissolved in chalcocite. On heating specimens of chalcocite containing inclusions of covellite, the areas that were originally covellite were converted into isometric, "blue" chalcocite, and as a result of an increase in volume, these areas had been raised, thereby imparting local relief. Since the specific volume of chalcocite is 0.1728 and that of covellite 0.2135, the conversion of covellite into chalcocite should have led instead to a reduction in volume. At 200° C the specific volume of "isometric" chalcocite is 0.193, which is reasonable for the intermediate composition, but does not explain the apparent relief. Bateman and Lasky stated that the increase in volume was not due to the internal pressure of sulfur in chalcocite, since this effect would be achieved only by a breakdown of the covellite to yield chalcocite and sulfur. This reaction was not apparent. On heating specimens in boiling water, a test for sulfur freed during the process of conversion was negative. The solution appeared to take place in one direction only, with the appearance of replacement by invading chalcocite.

"Ionic Migration" and "diffusion" were not inconceivable processes in this case, according to Bateman and Lasky. However, the fact that the covellite had undergone a volume increase was difficult to reconcile in view of the apparent solution of covellite in chalcocite, and *not* the converse.

The most systematic investigation of the low temperature fields of the systems Cu_2S-CuS was carried out by Newton W. Buerger (5), (6) in 1939 by means of *X*-rays. M. J. Buerger and Newton W. Buerger (7) also succeeded in clarifying the pre-existing relationships between low- and high-temperature chalcocite. The low form is apparently a superstructure that is based upon the structure of the high form, a basic hexagonal network of sulfur atoms containing copper atoms in disorder. The existence of the mineral phase, digenite, Cu_9S_5, which had been described as "isometric" and "blue" chalcocite on previous occasions, was clearly established by Newton W. Buerger. Rahlfs (20) had assigned what is now known as the digenite phase an antifluorite structure in which some of the copper atoms were thought to be statistically distributed over many different sites. This phase was shown by Newton Buerger to "dissolve" more CuS or Cu_2S at higher temperatures. An ordered phase having the "ideal composition", Cu_9S_5, was considered to prevail below 47° C.

The method used by Newton Buerger for developing the low temperature regions of the phase diagram for the system Cu_2S-CuS consisted essentially in homogenizing powdered mixtures of chalcocite and covellite. The

process involved pulverizing, compacting and annealing the material at 110° C for periods of twelve hours or longer.

On the basis of x-ray photographs taken at elevated temperatures Newton Buerger described the existence of three compounds, four phases and seven phase fields within the system Cu_2S-CuS. The compounds were:

Chalcocite, "ideally" Cu_2S
Digenite, "ideally" Cu_9S_5
Covellite, CuS

The phases were:

High-temperature chalcocite, hexagonal
Low-temperature chalcocite, orthorhombic
Digenite
Covellite

During investigations leading to the origin of chalcocite, Alfred D. Wandke (31) had recourse to repeat and enlarge upon several aspects of the work performed by Newton Buerger. Wandke contended that if powdered mixtures of chalcocite and covellite had been annealed for longer periods of time than Newton Buerger had allowed, more digenite would have been formed at the lower temperatures. Wandke also maintained that not all "blue" chalcocite is digenite since it had been found on x-ray examination to be structurally identical with anisotropic, white chalcocite.

To ascertain the mechanism by which digenite formed, Wandke devised a series of diffusion experiments. A cylinder, one-half centimeter in diameter, of pure, massive chalcocite from Keeweenau, Michigan was embedded in powdered, natural covellite in a tube, which was evacuated, sealed, and maintained at 110° C for 96 hours. The cylinder was weighed before and after the run and was found to have undergone a loss in weight of about 7.7% or theoretically, to have lost enough copper to have been altered to Cu_9S_5. The procedure was reversed using instead a cylinder of covellite that was surrounded by powdered chalcocite. On completion of the experiment, the cylinder exhibited a swelled and cracked appearance and appeared to have been transformed into digenite. Further studies were made on blocks of chalcocite and covellite, which were wired together and cut and polished across the interface to observe the minerals in contact. The blocks were placed in a pyrex tube that was evacuated, sealed, and maintained at 115° C for 24 hours. Afterwards, on repolishing the specimen, Wandke noted that the covellite, up to 1.7 mm from the contact, had lost its anisotropism and had been transformed into digenite. The chalcocite block had widened its cleavage due to a loss of volume over the surface. By repeating the procedure for another 24 hours, the digenite was found to have penetrated 3 mm deep into the covellite. Wandke described the front of attack as being "non-uniform" with the formation of "residuals of covellite like those in ores attributed to the replacement of covellite by digenite." X-ray photographs of the changed chalcocite and altered covellite indicated that both minerals had been transformed into digenite.

On the basis of his results, Wandke concluded that digenite was formed

not only by the diffusion of copper ions out of chalcocite, but also by the diffusion of copper ions into covellite. The equations given for the reactions were:

$$4\ Cu_{10}S_5 \rightarrow 4\ Cu_9S_5 + 4\ Cu$$
$$4\ Cu + 5\ CuS \rightarrow Cu_9S_5$$

whereby four moles of chalcocite are required to convert one mole of covellite to digenite.

According to Wandke (32), "blue" chalcocite or digenite can also be formed mechanically as a result of dragging and smearing when polishing specimens containing chalcocite, covellite, and digenite.

System: Cu-Fe-S.—A thorough study of the system Cu-Fe-S using only solid phases in equilibrium with sulfur vapor was performed by H. E. Merwin and R. H. Lombard (18) in 1937. Mattes, composed of varying amounts of iron and copper sulfides, were heated almost to melting under a sulfur vapor pressure of 455 mm. The phases synthesized were bornite (Cu_5FeS_4-Cu_5FeS_6), chalcopyrite ($CuFeS_2$), cubanite ($CuFe_2S_3$) and the compound ($Cu_3Fe_4S_6$). Cubanite and chalcopyrite enter into complete solid solution above 400° C. At this temperature, chalcopyrite, according to Newton W. Buerger and M. J. Buerger (8) is disordered, and on cooling reverts to the low ordered form by expelling cubanite or chalcopyrrhotite. Recent work by C. G. Cheriton (9) has indeed indicated that high-temperature chalcopyrite has a disordered sphalerite-type structure, which is capable of considerable solid solution.

In 1934, H. Borchert (3) studied some of the unmixing and stability relations in the systems Cu-Fe-S, using natural intergrowths of the phases chalcopyrite, bornite, and pyrrhotite. He indicated that chalcopyrite and bornite enter into solid solution above 500° C and that chalcopyrite forms a solid solution with chalcopyrrhotite ($CuFe_4S_6$) above 450° C. Below 255° C chalcopyrrhotite was found to be unstable and was transformed into cubanite at 235° C or valeriite at 225° C. Solid solutions of chalcopyrrhotite and pyrrhotite was found to unmix at 550° C with complete unmixing at 350° C. Chalcopyrite and bornite were found by Schwartz (23) to form extensive, but non-continuous solid solutions above the temperature 475° C.

Systems: Cu_2S-Sb_2S_3, Cu_2S-Bi_2S_3, PbS-Sb_2S_3, PbS-Bi_2S_3, Ag_2S-Sb_2S_3, Ag_2S-Bi_2S_3 and Sb_2S_3-Bi_2S_3.—A series of isothermal reduction decompositions of various mixed binary sulfides were achieved by R. Schenck, I. Hoffman, W. Knepper and Herbert Vögler (22) utilizing a hydrogen gas phase. From various H_2S degradation isotherms of the sulfide mixtures, the existence of the following phases listed in Table 1 was observed at 400° and 510° C. A reaction typifying the method, involved the reduction of Sb_2S_3, by hydrogen gas to form free antimony and hydrogen sulfide gas, as follows:

$$Sb_2S_3 + 3\ H_2 \rightarrow 2\ Sb + 3\ H_2S$$

The intermediate phases were formed by a recombination of the free metal, sulfur, and sulfides present, not by the mechanism of formation presented subsequently for the general case in which the role of a gas phase is relatively

unimportant. The examples are included as solid-state reactions permissible within the respective systems, cited. By using the measurements of the equilibrium H_2S/H_2 ratios in the gas phase, the free energies of formation were calculated by Carl Wagner (28). In the system Cu_2S-Sb_2S_3, the equilibrium free energy of formation, $\Delta F_{eq.}$ at 400° C of the phases, tetrahedrite and chalcostibite were calculated to be −725 and −787 calories per equivalent, respectively. In the system PbS-Sb_2S_3, $\Delta F_{eq.}$ for falkmanite and zinkenite were found to be −286 and −242 calories per equivalent, respectively.

RECENT SOLID-STATE INVESTIGATION AT LOW TEMPERATURES OF THE SYSTEMS: CU_2S-SB_2S_3, CU_2S-AS_2S_3, CU_2S-FES AND CU_2S-CUS

Acting on the premise that at relatively low temperatures, solid-state reactions could be generated to form intermediate sulfide phases in the systems: Cu_2S-Sb_2S_3, Cu_2S-As_2S_3, and Cu_2S-FeS, a series of experiments

TABLE 1

System	Temperature	Phases
Cu_2S-Sb_2S_3	400° C	Cu_2S (chalcocite), 2 or 3 $Cu_2S.Sb_2S_3$ (tetrahedrite), $5Cu_2S.Sb_2S_3$ (?), Cu_2S-Sb_2S_3 (chalcostibite), $4Cu_2S.5Sb_2S_3$ (?), $3Cu_2S.4Sb_2S_3$ (?), $2Cu_2S.3Sb_2S_3$ (?), Sb_2S_3 (stibnite).
Cu_2S-Bi_2S_3	510° C	Cu_2S (chalcocite), mixed crystals (wittichenite), (?); $3Cu_2S.2Bi_2S_3$ (klaprothite), $Cu_2S.Bi_2S_3$ (emplectite), $Cu_2S.2Bi_2S_3$ (?), $Cu_2S.3Bi_2S_3$ (?), Bi_2S_3 (bismuthinite).
PbS-Sb_2S_3	400° C	PbS (galena), $2PbS.Sb_2S_3$ (falkmanite), $5PbS.2Sb_2S_3$ (boulangerite), $5PbS.3Sb_2S_3$ (heteromorphite), $7PbS.5Sb_2S_3$ (warrenite), $5PbS.4Sb_2S_3$ (plagionite), $PbS.Sb_2S_3$ (zinkenite), Sb_2S_3 (stibnite).
PbS-Bi_2S_3	510° C	$6PbS.Bi_2S_3$ (beegerite), $3PbS.Bi_2S_3$ (lillianite), $PbS.Bi_2S_3$ (galenobismuthite), mixed crystals (galena and bismuthinite).
Ag_2S-Sb_2S_3	400° C	Ag(5Sb) (silver containing antimony), Ag_2Sb (antimony-silver), $2Ag_2S.Sb_2S_3$ (?) $4Ag_2S.3Sb_2S_3$ (?), $Ag_2S.Sb_2S_3$ (miargyrite), Sb(5Ag) antimony containing silver, Sb_2S_3 (stibnite).
Ag_2S-Bi_2S_3	510° C	Ag (silver), Ag_2S-(argentite), (silver-bismuth melt), (liquid bismuth), $5Ag_2S.4Bi_2S_3$ (schapbachite), $Ag_2S.Bi_2S_3$ (plenargyrite-matildite), $3Ag_2S.4Bi_2S_3$ (silver-bismuthinite), Bi_2S_3 (bismuthinite).

were undertaken by the author as partial fulfillment of the Ph.D. requirement in Geology at the Massachusetts Institute of Technology.

The methods used to synthesize the various intermediate phases were adopted and modified from previous work on the system Cu_2S-CuS that was undertaken by Posnjak, Allen and Merwin (19) and later by Newton W. Buerger (5). The experimental procedure consisted in taking x-ray powder photographs at elevated temperatures of compacted mixtures of the pure sulfides, which had been annealed at 110° C for 24 hours and in the case of the system Cu_2S-FeS at 150° C for the same duration of time. The chalcocite, which was extremely pure and of hypogene origin, used during the investigation had been collected from the Baltic Lode of the Champion mine, Keeweenau, Michigan by Alfred D. Wandke, Jr. during his investiga-

tion of the origin of chalcocite. The results of the four systems studied were found to be of comparable accord with regard to the formation of cuprian-, antimonian-, ferroan-, and arsenoan-chalcocite solid solutions, and cupro-, stibio-, ferro-, and arseno-digenite solid solutions. The isostructural nature of these solid solutions was evident from the *X*-ray photographs.

At equilibrium in the system Cu_2S-Sb_2S_3 below 125° C, the following solid solutions were encountered in the direction of increasing Sb_2S_3 content: antimonian-chalcocite, stibiodigenite, and cuproan-stibnite. At higher temperatures, from 125° to 200° C, the phases tetrahedrite, Cu_3SbS_3, and chalcostibite, $CuSbS_2$, were observed to form in equilibrium with chalcocite and stibnite. The phase relations between the latter and the low temperature digenite shall be described in a forthcoming publication.

In the system Cu_2S-As_2S_3 at low temperatures, the phases arsenoan-chalcocite, arsenodigenite, and orpiment were found to occur at equilibrium. The phases ferroan-chalcocite, ferrodigenite, bornite and pyrrhotite were observed to coexist at equilibrium in the system Cu_2S-FeS at low temperatures. In the system Cu_2S-CuS according to Newton Buerger the phases occurring at equilibrium are cuprian-chalcocite (solid-solution), cuprodigenite, and covellite.

Comparison of the Chalcocite and Digenite Phases.—The antimonian-, arsenoan-, ferroan- and cuprian-chalcocite solid solutions were observed to be homogeneous, white to light gray (weakly anisotropic to isotropic) in polished sections. With increasing sulfur content the x-ray patterns of these phases were observed to be very similar to those of high-temperature (hexagonal) chalcocite.

The phases stibio-, arseno-, and ferro-digenite were observed to be isostructural with the cuprodigenite found by Newton W. Buerger during his investigation of the system Cu_2S-CuS. In reflected light cuprodigenite is light blue in color, but stibiodigenite appears gray, and arseno- and ferrodigenite are brownish-gray. The differences are due apparently to the individual reflecting powers of the substituting atoms in each case.

A comparison of the digenite phases of the various systems according to composition and temperature of formation indicates that the ideal composition lies near or about a metal to sulfur ratio of 1.8:1.

System	Minimum temperature	Ideal composition	Ratio metal:sulfur
Cu_2S-CuS	47° C *	Cu_9S_5 *	1.80:1
Cu_2S-As_2S_3	55° C	$Cu_{18}AsS_{11}$	1.82:1
Cu_2S-Sb_2S_3	67° C	$Cu_{18}SbS_{11}$	1.82:1
Cu_2S-FeS	125° C	$Cu_{81}Fe_7S_{50}$	1.84:1

* After Newton W. Buerger.

There appears to be a partial correlation between the minimum temperature of formation of digenite having the ideal composition and the melting points of the pure sulfides. The list includes two reported decompositions temperatures for covellite.

Covellite, CuS	220° C, 360° C
Orpiment, As_2S_3	300° C (m.p.)
Stibnite, Sb_2S_3	545° C (m.p.)
Pyrrhotite, FeS	1163° C (m.p.)

A relation, developed by Braune (4) expresses that the rate of diffusion in mixed crystals varies inversely and exponentially with the absolute temperature of melting. The latter is based upon Lindemann's theory that melting occurs when the average amplitude of the atomic vibrations reaches a critical value. The ability to enter into solid state reactions is apparently increased on approaching the melting temperature, in general, but is more closely related to the presence of a thermal inversion, such as disordering of the copper and iron atoms in chalcocite at 105° C and pyrrhotite at 138° C, respectively. No thermal inversion in this temperature range is known for stibnite or orpiment; however, an amorphous, red phase of Sb_2S_3, described as metastibnite by G. M. Schwartz (24) can be transformed into crystalline stibnite at 200° C under pressure.

A type of cupro-ferro-digenite is known to occur in nature as a result of the replacement of bornite by chalcocite. The minimum temperature of formation of this phase was recorded by G. M. Schwartz (25) as 100° C, which is roughly half-way between the minimum temperatures recorded for the pure cupro- and ferro-digenites.

The low-temperature phase in the system Cu_2S-FeS designated as a type of bornite appears to be similar to the high-temperature form of bornite reported by Alfred J. Frueh (12). This phase remained stable indefinitely at ordinary temperatures. The transformation between digenite and the bornite type phase was observed in each case to be highly reversible and reproducible. In the case of natural bornite, the high-temperature form could not be preserved by quenching below 220° C but was always found to revert. On heating the bornite-type phase of higher sulfur content to 300° C, it was not observed to transform into ferro-digenite.

From samples in the system Cu_2S-FeS that were heated at 200° C in the presence of argon gas at one atmosphere for periods of five to seven days, it was still impossible to obtain a more complete reaction in the solid state to form the "prototypes" of chalcopyrite, cubanite, and Merwin's compound.

The digenite phases can vary extensively in composition by "assimilating" more sulfur or cuprous copper ions at higher temperatures. There also seems to be little limitation on the nature of the substituted polyvalent metal atoms. Solid state reactions between chalcocite and other minerals such as galena, bismuthinite, and numerous lead, antimony, arsenic, iron and bismuth sulfosalts and complex sulfides should be possible at relatively low temperatures.

MECHANISM OF FORMATION OF THE INTERMEDIATE SULFIDE PHASES

The formation of the various intermediate or ternary sulfide phases, such as digenite, that were synthesized in the systems Cu_2S-CuS, Cu_2S-Sb_2S_3, Cu_2S-As_2S_3 and Cu_2S-FeS involved reactions in the solid state at temperatures far below melting. The reaction phenomena might well be described as "*solid solution*," but this term should be used *only* in the strict thermodynamic sense to denote the resultant intermediate phase, since formation can be achieved not only by diffusion in the solid state, but also through the action or solidification of a liquid phase.

The interactions of the various sulfides and chalcocite in this case appear to be comparable with the observed diffusion in such systems as Cu_2S-Ag_2S and NaCl-AgCl, etc., where there is a common anionic constituent of almost negligible mobility. In this respect, W. Jost (16) has drawn an analogy between diffusion in solid "ionic-type" crystals and the diffusion of ions in the solution of an electrolyte. However, in the case of electrolytic solutions, the cations all move towards the negative pole, but in the case of diffusion in solid "ionic-type" crystals, the mobile constituents, metal ions, flow in opposite directions in order to preserve electric neutrality.

The equation for the general case involving the formation of an intermediate sulfide phase, where the metal constituents diffuse as "ions" and the mobility of the sulfur atoms is almost negligible, is as follows:

$$MS + M'S \rightarrow MM'S_2.$$

The equations for flow of metal "ions," M and M', of concentrations, C and C', in the presence of both a concentration gradient and a potential gradient $\frac{\partial \phi}{\partial x}$ are:

$$J_M = - u_M \left(kT \frac{\partial C}{\partial x} - Ze_M C \frac{\partial \phi}{\partial x} \right)$$

$$J_{M'} = - u_{M'} \left(kT \frac{\partial C'}{\partial x} - Ze_{M'} C \frac{\partial \phi}{\partial x} \right)$$

where u is the ionic mobility of the cation, equal to the velocity in unit electric field in e.u. and Ze is the charge on the cation. The latter term in the equations for flow refers to the current caused by the diffusion potential ϕ which arises as a result of the different mobilities of the metal ions. Since $C + C'$ is constant,

$$\frac{\partial C}{\partial x} = - \frac{\partial C'}{\partial x}$$

Electric neutrality requires that the total rate of transport be equal to zero; hence setting

$$J_M = - J_{M'},$$

the potential gradient,

$$\frac{\partial \phi}{\partial x} = - \frac{(u_M + u_{M'})}{(u_M CZe + u_{M'} C' Ze_{M'})} \cdot \frac{\partial C'}{\partial x} \cdot kT$$

Substituting for $\frac{\partial \phi}{\partial x}$ in the equations of flow,

$$J_M = - J_{M'} = - kT \frac{\partial C}{\partial x} u_M u_{M'} \cdot \frac{(CZe_M + C'Ze_{M'})}{(u_M CZe_M + u_{M'} C' Ze_{M'})}$$

which is identical to the Nernst equation for the diffusion of ions in solutions

of electrolytes. From the Nernst-Einstein relation for the coefficient of diffusion,

$$D = ukT$$

$$D_{MM'} = u_M u_{M'} kT \cdot \frac{(CZe_M + C'Ze_{M'})}{(u_M CZe_M + u_{M'} C'Ze_{M'})}$$

is finally obtained. By allowing N_M to represent the fraction,

$$\frac{CZe_M}{CZe_M + C'Ze_{M'}}$$

and similarly for $N_{M'}$, an average mobility is obtained:

$$u_{MM'} = \frac{u_M u_{M'}}{N_M u_M + N_{M'} u_{M'}}$$

Consequently, the average coefficient of diffusion may be represented as follows:

$$D_{MM'} = u_{MM'} kT.$$

The equation for the coefficient of diffusion has been presented to illustrate the effects of the mobilities of the two types of metal atoms ("ions") on the overall rate of diffusion for the case where the mobility of the sulfur atoms is so slight as to be neglected. On the basis of diffusion experiments on chalcocite and covellite, A. D. Wandke (31) concluded that digenite was formed as the result of not only the diffusion of copper ions out of chalcocite, but also by the diffusion of copper ions into covellite. In order to preserve electric neutrality during the process of diffusion Wandke's equations could be modified in the following manner to allow for the transfer of electrons:

$$20\ Cu_2S \longrightarrow 4\ Cu_8CuS_5 + 4\ Cu^+ + 4\ e$$

$$5\ CuS + 4\ Cu^+ + 4\ e \rightarrow Cu_8CuS_5$$

so that

$$4\ Cu_2S + CuS \longrightarrow Cu_9S_5$$

the diffusion of copper ions would, in this case, be accompanied by the simultaneous flow of electrons in the same direction. Owing to the availability of free electrons in chalcocite, this flow of ions and electrons is not inconceivable. However, as more moles of covellite are affected this phenomenon should ultimately give way to the simultaneous and chemically-equivalent interchange of cuprous and cupric ions. The mechanism is depicted in Figure 1 for the formation of a hypothetical intermediate sulfide, phase, $MM'S_2$.

The increased weight and volume of the covellite phase can be adequately accounted for by the 2:1 transport ratio of cuprous to cupric ions:

$20\ Cu_2S$	$4\ Cu_6S_5$	Cu_9S_5	$5\ CuS$

$\longrightarrow 8\ Cu^{+} \longrightarrow$

$\longleftarrow 4\ Cu^{++} \longleftarrow$

Phase boundary reaction	Phase boundary reaction
$20\ Cu_2S$	$5\ CuS$
$-\ 8\ Cu^{+}$	$-4\ Cu^{++}$
$+\ 4\ Cu^{++}$	$+8\ Cu^{+}$
$=\ 4\ Cu_8CuS_5$	$=\ Cu_8CuS_5$
$=\ 4\ Cu_9S_5$	$=\ Cu_9S_5$

It should be possible to obtain the ionic mobilities for such systems as $Cu_2S-Sb_2S_3$, etc., from measurements of the electrolytic conductivities and transference numbers from an appropriate galvanic cell. Such a cell might closely resemble a horizontal cross-section of the equilibrium distribution of the phases contained in the phase diagrams of the systems. During

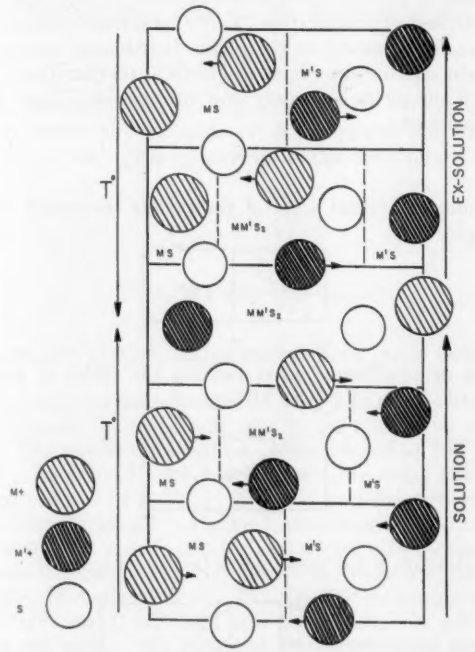


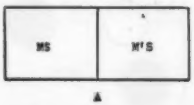
FIG. 1. The mechanism of formation and reverse process of ex-solution of an intermediate phase, $MM'S_2$, in the solid state.

this investigation, no direct determination was made of the coefficients of self-diffusion of copper in chalcocite. However, a few experiments were carried out to measure the relative rates of formation of the intermediate phases, which are functions of the coefficients of diffusion. The rate data bear directly on the formation of intermediate phases in ore deposits.

Determination of the Relative Rates of Formation of the Intermediate Phases.—The method used to determine the relative rates of formation of the intermediate phases in the systems studied, was adopted essentially from Tammann and Roche (26). Fine powders, about 250 to 300 mesh, of the pure sulfides were compressed into single pellets, each consisting of one-half chalcocite and one-half either covellite, stibnite, orpiment, or pyrrhotite. Each pellet measured one-quarter of an inch in diameter and about three-eighths of an inch in length. The four pellets, representing the four systems studied, were placed in one arm of a long, U-shaped, pyrex glass tube. The pellets were separated from each other by means of short glass rods. The tube assembly was connected to a slow, steady stream of nitrogen gas, and then placed within a muffle furnace for runs at 130° C and 200° C for different lengths of time. Since each pellet was composed of the end-member sulfides in each of the systems studied, it was expected that after time, t, had elapsed at temperature, T, the long cross-sections of the pellets would be in reality a model of the phase distribution contained along the horizontal of the equilibrium phase diagrams at temperature, T. Assuming for the sake of simplicity that only one intermediate phase is formed as a result of the reaction:

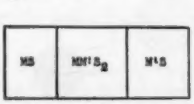
$$MS + M'S \rightarrow MM'S_2$$

and representing the initial state of the pellets composed of sulfides, MS and $M'S$ (Figure 2A),



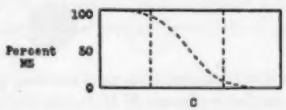
A

the final state of equilibrium after heating the pellet at temperature, T, for time, t, would be as in Figure 2B.



B

The concentration of MS is assumed to be as in Figure 2C.



C

In accordance with Fick's Law, the quantity of ions or atoms, M, diffusing across the interface in time, dt,

$$dn = D_M \cdot A \frac{\Delta C}{x} \cdot dt$$

where D_M is the diffusion coefficient, A, the area of cross section and $\frac{\Delta C}{x}$, the concentration gradient in the intermediate phase, assumed to be linear. Since dn corresponds to a proportionate increase in the thickness, dx, of the intermediate phase,

$$dn = b \cdot A \cdot dx$$

Substituting for dn, and integrating,

$$\tfrac{1}{2}x^2 = D_M \cdot \frac{\Delta C}{x} \cdot t$$

If the quantities, D_M, b, and C are not determined separately, they can be consolidated into k, the rate constant, measured in $cm^2\ sec^{-1}$. The result is Tammann's Parabolic Rate Rule for the thickness of the intermediate phase,

$$x = (2k \cdot t)^{\frac{1}{2}}.$$

If the previous assumptions regarding diffusion are correct, a plot of the thickness of the intermediate phase versus the square root of time should yield essentially a straight line. From the crude assumption that:

$$k_1 = C \exp \frac{(\Delta E)}{kT_1}$$

and

$$k_2 = C \exp \frac{(\Delta E)}{kT_2}$$

the average activation energy, ΔE, of intermediate phase formation can be calculated.

Discussion of Experimental Results.—Following each run, the individual pellets were mounted in lucite, cut lengthwise normal to the interface, and polished. The results obtained for pellets heated at 200° C are shown in Figures 3–6. In Table 2 are listed the data describing the intermediate phases and their rates of formation. The values of the rate constant k that were obtained from the graph in Figure 7, were found to be high compared with various systems of metals in which alloys form by diffusion. Within the limits of time indicated, the thickness of intermediate phase formation was found to vary linearly with $t^{\frac{1}{2}}$. The average activation energy, E for the systems, Cu_2S-CuS, Cu_2S-Sb_2S_3 and Cu_2S-As_2S_3 was calculated to be 7.9 kilocalories per mole. No values of k were obtained for the system, Cu_2S-FeS due to the physical separation of the primary phases and the irregular phase boundaries. The rates of formation of the intermediate

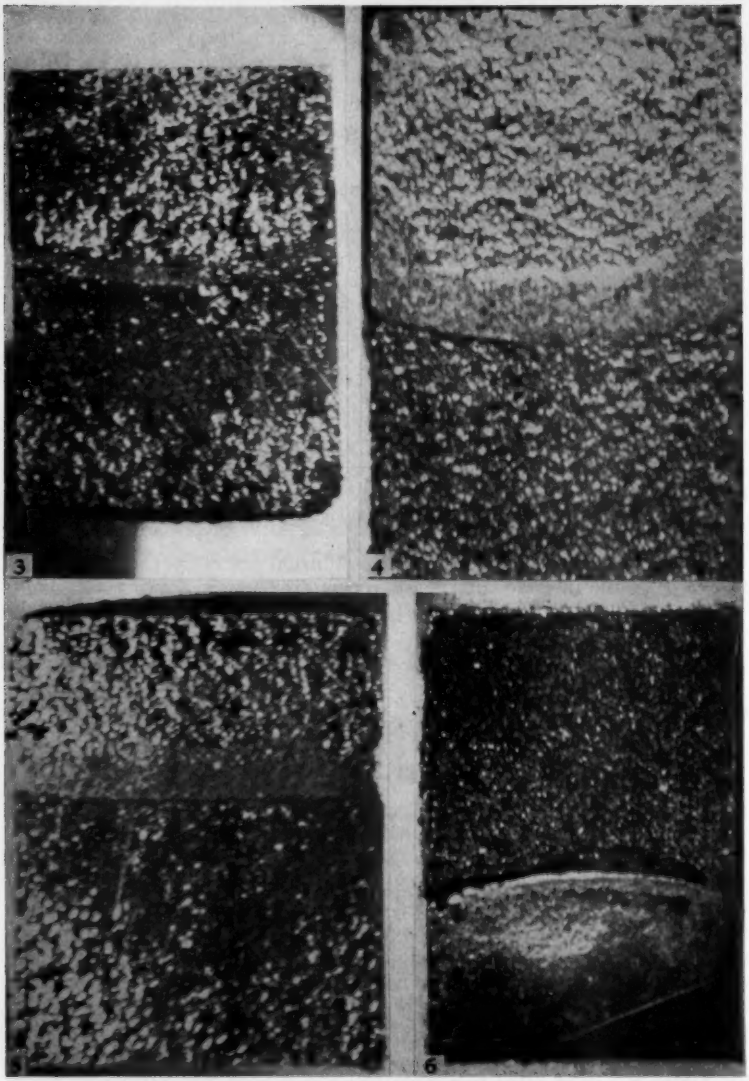


FIG. 3. Intermediate phase formation in the system Cu_2S-Sb_2S_3: 200° C, 24 hrs.
FIG. 4. Intermediate phase formation in the system Cu_2S-Sb_2S_3: 200° C, 64 hrs.
FIG. 5. Intermediate phase formation in the system Cu_2S-CuS: 200° C, 48 hrs.
FIG. 6. Intermediate phase formation in the system Cu_2S-FeS: 200° C, 64 hrs.
(Lowest member in each figure denotes chalcocite).

phases in this system were found to be somewhat lower than those of the other systems.

In the systems Cu_2S-Sb_2S_3, Cu_2S-As_2S_3 and Cu_2S-FeS, the intermediate phases were found to differ in both texture and reflectivity from the binary sulfides, but in the system Cu_2S-CuS the original textures of the chalcocite and covellite were greatly preserved. It is doubtful that these structures would have been preserved, had both the copper and sulfur ions migrated at appreciable rates.

Conclusions.—The experiments have indicated that the rates of intermediate phase formation at low temperatures are appreciable in these

TABLE 2

TABLE OF RESULTS OF INTERDIFFUSION EXPERIMENTS

MS-M'S system	Temp.	Time	Thickness of intermediate phase (*s*)	Nature of intermediate phase (*s*)	Nature of chalcocite	Nature of *M'S*	$\sqrt{k}$, $cm^2 sec^{-1}$ rate constant
Cu_2S-CuS	200° C	48 hrs	1.2 mm	Digenite (½ replaced chalcocite, ½ replaced covellite), isotropic, white	Weakly anisotropic, white	Strongly anisotropic, blue	2.0×10^{-6}
		48 hrs	1.15 mm				
		36 hrs	0.8 mm				
		30 hrs	0.6 mm				
		24 hrs	0.4 mm				
	130° C	72 hrs	1.1 mm				
		48 hrs	0.8 mm				5.2×10^{-8}
Cu_2S-Sb_2S_3	200° C	64 hrs	1.1 mm	Chalcostibite, digenite, and residual stibnite	Weakly anisotropic, blue	Strongly anisotropic, white	5.3×10^{-7}
		48 hrs	0.9 mm				
		24 hrs	0.4 mm				
	130° C	72 hrs	0.1 mm				1.4×10^{-8}
		48 hrs	0.05 mm				
Cu_2S-As_2S_3	200° C	64 hrs	0.8 mm	Digenite and residual orpiment	Weakly anisotropic, blue	Anisotropic, yellow-white	3.9×10^{-7}
		48 hrs	0.6 mm				
		24 hrs	0.3 mm				
	130° C	72 hrs	0.05 mm				9.5×10^{-9}
		48 hrs	0.01 mm				
Cu_2S-FeS	200° C	96 hrs	Irregular boundaries with separation of initial phases	Digenite and irridescent phase (*s*) unidentified	Weakly anisotropic, white	Anisotropic, gray-white	—
		64 hrs					
		24 hrs					
	130° C	72 hrs					—
		48 hrs					

systems; hence, considerable importance should be attached to the role of solid-state diffusion in ore deposits.

The diffusion process appeared to be in compliance with Tammann's Parabolic Rate Rule, which seems to offer evidence that the stoichiometric relations between the *sulfides* and *sulfosalts* may be correlated with those between *metals* and their *alloys*. L. Eisenmann (10) classifies chalcocite as a semi-conductor, and digenite and covellite as metallic conductors. In the system Cu_2S-CuS the specific resistance decreased with increasing CuS at room temperature. An abrupt change in the resistance was encountered at the composition $Cu_{1.8}S$ (digenite). A similar pronounced effect was observed by Kushida (17) at 550° C.

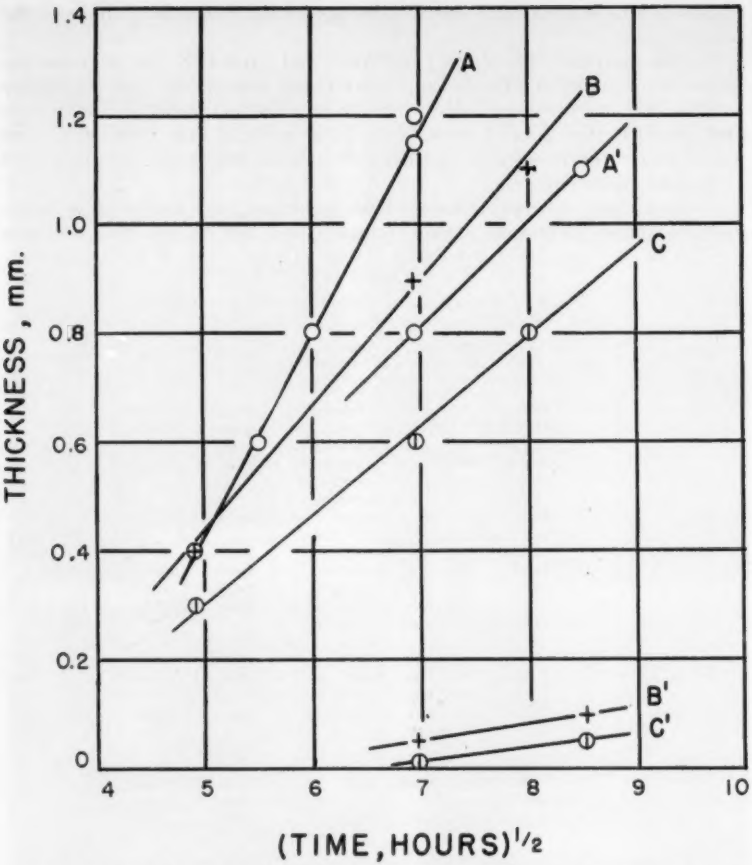


FIG. 7. Graph showing rate-constant curves obtained by plotting the intermediate phase thickness versus time at temperatures 200° C and 130° C for the systems: Cu_2S-CuS—A, A′; Cu_2S-Sb_2S_3—B, B′; Cu_2S-As_2S_3—C, C′.

The mechanism of metal migration through an intermediate phase is similar to the diffusion of copper through copper sulfide as observed by Fischbeck and Dorner (11) and silver in the system Ag_2S-S and other cases treated by Wagner (29), (30). The formation of Ag_2Se (naumannite) and Ag_2Te (hessite) by silver ion migration has been similarly discussed by Tubandt, Reinhold, and Neumann (27). The validity of the Einstein equation, $D = ukT$, Wagner contends, holds only if self-diffusion is accomplished by the random movement of atoms in vacancies or interstitial

positions. Such lattice defects as interstitial ions, cation and anion vacancies, free electrons, and quasi-electron holes may lead to the migration of both metal ions and electrons, which travel in the same direction. The activation energy of synthetic chalcocite was observed by Hirahara (14) to be related to the sulfur deficiency or excess. Chalcocite has been shown to have exceptionally low activation energies for electrolytic conduction and diffusion, on the order of a few kilocalories per mole. The coefficients of self-diffusion of copper in chalcocite were found to be on the order of 10^{-9} to 10^{-7} cm^2/sec by M. L. Jensen (15). The higher figure was obtained above the inversion temperature of chalcocite.

According to Hirahara (13) there are three forms of cuprous sulfide (chalcocite): a low-temperature form stable below 110° C, which can be described as a P-type semi-conductor; an intermediate form stable between 110° and 470° C, which exhibits a sharp decrease in electronic current and a remarkable ionic conductivity; and a third form, stable beyond 470° C with slight ionic and very great electrical conductivity. The existence of atoms in disorder within fairly stable anionic networks as in the case of high-temperature chalcocite, argenite, bornite, chalcopyrite and related simple and complex sulfides, selenides, tellurides and oxides make feasible the formation of innumerable complex minerals. Solid-state reactions are possible, provided the proper boundary conditions and temperatures exist to supply the necessary chemical and electrical potentials.

RELATION TO "UN-MIXING" AND "EX-SOLUTION" PHENOMENA

The "ex-solution" or "un-mixing" of high-temperature complex sulfides to yield more stable low-temperature forms as observed by Bateman (2) for chalcocite-covellite intergrowths; by Borchert (3) for various copper-iron sulfides; and by A. C. Spencer for bornite-chalcocite intergrowths must proceed in very much the same but reverse manner, with metal ions moving in very opposite directions. Since the separation of the resultant phases occurs along specific planes, these are very likely normal to the directions of preferred migration, across the commonly shared plane of sulfur atoms. The separation of covellite along the (111) planes of digenite during "ex-solution" is a typical example. The hypothetical case involving the formation and "ex-solution" of an intermediate sulfide phase, $MM'S_2$ is shown in Figure 1.

GEOLOGICAL SIGNIFICANCE

As a result of the X-ray investigation of the systems Cu_2S-CuS, Cu_2S-Sb_2S_3, Cu_2S-As_2S_3 and Cu_2S-FeS, a general theory of formation of intermediate sulfide phases has been developed to explain the solid-state reactions involved. Since the formation of these phases has been observed to proceed at appreciable rates in the laboratory, it is not unlikely to presuppose that similar intermediate phases can develop in ore deposits containing chalcocite at moderate to great depths at temperatures beyond the temperature of initial disorder of chalcocite (i.e. above 70° C). In compliance with Tammann's Parabolic Rate Rule, a rate constant of the order of

10^{-8} cm^2/sec^{-1} at 130° C implies that as much as 8 centimeters of digenite could be formed over a period of 100 years in a deposit located at moderate to great depths.

The role of solid-state diffusion shortly after the deposition of an ore body must be significantly great at the prevailing temperatures, and equilibrium is probably established within a short period. The role of solid-state diffusion during thermal metamorphism and the reworking of deposits by solutions, should be extensive. In cases where the "order of solubility" does not appear to be a usable criterion for replacement, solid-state diffusion may be responsible for the formation of complex phases. Sales and Meyer (21) reporting on the effect of post-ore dike intrusion on Butte minerals, showed fields that suggested the "progressive replacement of bornite by invasion of chalcocite" while the formation of the bornite was actually due to the "thermal metamorphism of a pyrite-bearing chalcocite ore." The distinction between primary and secondary digenite may also be difficult to ascertain, since digenite can be preserved by quenching solid solutions formed from the cooling of melts. Concerning the origin of deposits containing chalcocite, Bateman and Lasky (1) declared that the presence of "isometric" chalcocite (digenite) is not to be regarded as "prima facie" evidence of hypogene rather than secondary origin, since orthorhombic chalcocite could occur alone from solutions of hypogene origin at temperatures less than 90° C. In other words the temperature is not the sole determining factor as is the nature of the mineral association. While it is often possible to establish a minimum temperature of formation when digenite is present, it may be unwise to speculate on the processes of formation unless there is direct evidence of "ex-solution" or replacement.

On the basis of the results obtained for the systems Cu_2S-Sb_2S_3 and from the similar chemical properties of antimony and bismuth, it appears likely that chalcocite and bismuthinite, Bi_2S_3, would react in the solid state to form bismodigenite, $Cu_{19}BiS_{11}$; klaprotholite, $Cu_6Bi_4S_9$; cuprobismuthinite, $CuBiS_2$: and wittichenite, Cu_3BiS_3 given sufficient time for the diffusion to proceed at temperatures in the vicinity of 100° C. Furthermore, it seems highly plausible that the reactions which have been achieved with chalcocite, Cu_2S, could be duplicated for acanthite, Ag_2S which disorders thermally and inverts at 179° C. Extensive solid solutions in the system Cu_2S-Ag_2S are known to form in the solid state.

Since the rates of diffusion in the binary systems can be closely correlated with the average rates of metal ion self-diffusion, it is apparent that self-diffusion of antimony, arsenic, iron and copper ions in stibnite, orpiment, pyrrhotite, and covellite, respectively, is appreciably great in the range of relatively low temperatures. Reactions at low temperatures between these sulfides and others like galena, which is composed of highly polarizable lead atoms, may be possible. Similarly, interactions between sulfosalts and complex sulfides, selenides, tellurides and oxides of the transitional and Group B metals should be feasible in the solid state at low temperatures. More detailed examination of ore specimens containing intermediate phases, such as the ternary sulfides, may serve to indicate that these phases were

formed in completely closed systems. The high prevalence of these intermediate phases and the corresponding rarity of such minerals, as stibnite, orpiment, and bismuthinite in the same deposits may be due in part to complete "assimilation" in the solid state to form the more stable intermediate phases by diffusion.

ACKNOWLEDGMENTS

The major portion of the research was conducted at the Massachusetts Institute of Technology as partial requirement for the Ph.D. thesis. The author is grateful to Professor M. J. Buerger as thesis advisor for critical suggestions during the investigation and on reading the manuscript. Professor Carl Wagner generously supplied direction to the research through valuable discussions.

Supplementary research was achieved at Yale University under a grant of the Shell Fund for Fundamental Research in Geology through the support and encouragement of Professor Alan M. Bateman.

REFERENCES

1. Bateman, Alan M., and Lasky, Samuel G., 1932, Covellite-chalcocite solid solution and exsolution: Econ. Geol., **27**, p. 52.
2. Bateman, Alan M., 1929, Some covellite-chalcocite relationships: Econ. Geol., **24**, p. 424.
3. Borchert, H., 1934, Über entmischungen im system Cu-Fe-S und ihre bedeutung als geologische thermometer: Chemie der Erde, **9**, p. 145.
4. Braune, H., 1924, Über diffusion in mischkristallen: Zeit. für phys. Chem., **110**, p. 147.
5. Buerger, Newton W., 1939, An X-ray investigation of the solid phases of the systems Cu_2S-CuS: Ph.D. Thesis, Department of Geology, Massachusetts Institute of Technology.
6. Buerger, Newton W., 1942, X-ray evidence for the existence of the mineral, digenite, Cu_9S_5: Amer. Min., **27**, p. 712.
7. Buerger, M. J., and Buerger, Newton W., 1944, Low chalcocite and high chalcocite: Amer. Min., **29**, p. 55.
8. Buerger, Newton W., and Buerger, M. J., 1934, Crystallographic relations between cubanite segregation plates, chalcopyrite matrix, and secondary chalcopyrite twins: Amer. Min., **19**, p. 289.
9. Cheriton, C. G., 1952, Ph.D. Thesis, Department of Geology, Harvard University.
10. Eisenmann, L., 1952, Elektrisches und optisches verhalten der kupfersulfide: Ann. der Phys. **10**, p. 129.
11. Fischbeck, K., and Dorner, O., 1929, Der spezifische widerstand des kupfersulfids und sein temperaturkoeffizient: Zeit. für anorg. und allgem. Chem., **181**, p. 372.
12. Frueh, Jr., Alfred J., 1950, Disorder in the mineral, bornite, Cu_5FeS_4: Amer. Min., **35**, p. 185.
13. Hirahara, Eiji, 1951, The physical properties of cuprous sulfides-semi conductors: Jour. of Phys. Soc. of Japan, **6**, p. 422.
14. ——, 1951, The electrical conductivity and isothermal hall effect in cuprous sulfide, semiconductor: Jour. of Phys. Soc. of Japan, **6**, p. 428.
15. Jensen, Mead Leroy, 1951, Diffusion in minerals: Ph.D. Thesis, Department of Geology. Massachusetts Institute of Technology.
16. Jost, W., 1952, Diffusion in solids, liquids, and gases, Academic Press, Inc., New York.
17. Kushida, Toshimoto, 1952, On the variation of high-temperature conductivity of cuprous sulfide with sulfur vapour pressure: Jour. of Sci. of Hiroshima University, Ser. A, **16**, p. 75.
18. Merwin, H. E., and Lombard, R. H., 1937, The system Cu-Fe-S: Econ. Geol., **32**, p. 203.
19. Posnjak, E., Allen, E. T., and Merwin, H. E., 1915, The sulfides of copper: Econ. Geol., **10**, p. 491.
20. Rahlfs, P., Über die kubischen hochtemperaturmodifikationen der sulfide, selenide, und telluride des silbers und des einwertigen kupfers: Zeit. für phys. Chem. (B), **31**, 1936, p. 157.
21. Sales, R. H., and Meyer, C., 1951, Effect of post-ore dike intrusion on Butte minerals: Econ. Geol., **46**, p. 813.

22. Schenck, R., Hoffmann, I., Knepper, W., and Vögler, H., 1939, Gleichgewichtsstudien über erzbildende sulfide, I: Zeit. für anorg. und allgem. Chem., 240, p. 173.
23. Schwartz, G. M., 1942, Progress in the study of ex-solution in ore minerals: Econ. Geol., 37, p. 345.
24. Schwartz, G. M., 1932, Method of making synthetic minerals for polished surface study, Amer. Min., 17, p. 478.
25. Schwartz, G. M., 1928, Experiments on bornite-chalcocite intergrowths: Econ. Geol., 23, p. 381.
26. Tammann, G., and Roche, H. J., 1931, Die diffusion zweiter metalle ineinander unter bildung intermetallischer verbindung: Zeit. für anorg. und allgem. Chemie, 199, p. 289.
27. Tubandt, C., Reinhold, H., and Neumann, A., 1933, Über elektrizitatsleitung und diffusion in festem silbersulfid, -selenide und -telluride und über den mechanismus der bildung dieser verbindungen aus den elementen: Zeit. für Elektrochem., 39, p. 227.
28. Wagner, C., Thermodynamics of the systems Sb_2S_3-PbS and Sb_2S_3-Cu_2S: unpublished.
29. Wagner, C., 1933, Beitrag zur Theorie des Anlaufergangs: Zeit. für phys. Chem., (B), 21, p. 25.
30. Wagner, C., 1952, The electrochemistry of ionic crystals: Jour. of Electro. Chem. Soc., 99, p. 346 C.
31. Wandke, Jr., Alfred D., 1950, Investigations leading to the origin of chalcocite: Ph.D. Thesis, Department of Geology, Harvard University.
32. Wandke, Jr., Alfred D., 1953, Polishing phenomena in the copper sulfides: Econ. Geol., 48, p. 225.

THE OCCURRENCE OF COBALT AND NICKEL IN THE SILVER SUMMIT MINE COEUR D'ALENE DISTRICT, IDAHO[1]

VERNE C. FRYKLUND, JR., AND MURL W. HUTCHINSON

CONTENTS

	PAGE
Abstract	753
Introduction	753
Previous geologic work in the Silver Belt	754
Summary of regional geology	754
Summary of geology of the Silver Summit mine	755
Summary of mineralogy of the tetrahedrite veins	755
Occurrence of gersdorffite	756
Sequence of formation of the veins and ore shoots	757
Conclusions	757
Acknowledgments	758
Bibliography	758

ABSTRACT

Cobalt and nickel of possible commercial interest have been discovered in the Silver Summit mine, Coeur d'Alene district, Idaho. Assay data indicate that an ore shoot contained about 0.40 percent cobalt and about 1.0 percent nickel in addition to the copper and rich silver ores. The cobalt-nickel mineral gersdorffite occurs in tetrahedrite-siderite veins. Gersdorffite is widespread in small amounts and appears to have been the first of the "ore shoot" minerals. The known occurrence of either cobalt bloom or gersdorffite in other properties of the Coeur d'Alene district Silver Belt suggests that other ore shoots may exist that contain commercial quantities of cobalt and nickel.

INTRODUCTION

THE occurrence of cobalt and nickel in the Coeur d'Alene district was first recognized by Willard (17a, 17b), who, on the basis of etch and microchemical tests, identified gersdorffite (Ni, Co, Fe) AsS in ore from the Polaris mine. This identification has been recently confirmed by X-ray analysis.

The present study, part of the U. S. Geological Survey's Coeur d'Alene project, was started with the aid of the Polaris Mining Company, after abundant cobalt bloom was noted on the 3,000 level of the Silver Summit mine. Conventional cobalt assays were made at the Calera Mining Company assay laboratory; nickel determinations were made by the Geological Survey using geochemical prospecting techniques. The samples analyzed were reject pulps of channel samples taken as the workings were being driven; consequently they

[1] Publication authorized by the Director, U. S. Geological Survey.

were fresh and contained no oxidized material. Drift samples, combined with raise samples, indicate that one small ore body contained about 0.40 percent cobalt and about 1.0 percent nickel in addition to the copper and rich silver ores. A tetrahedrite mill concentrate contained 0.52 percent cobalt; nickel was not determined. This is the first ore shoot in the Coeur d'Alene district known to contain amounts of cobalt and nickel of possible commercial interest.

The ore shoot has now been very nearly mined out and the following remarks constitute a post-mortem report that would have little value if the ore shoot were in a small mine in a small district. The Silver Belt of the Coeur d'Alene district, however, is being actively mined and explored by several companies and other tetrahedrite-rich ore shoots will quite probably be discovered that might contain quantities of cobalt and nickel sufficient to make their recovery of possible economic importance.

Location.—The Coeur d'Alene district is in the panhandle of northern Idaho. The Silver Summit mine is in the heart of the district about 2 miles west of Osburn and 5 miles east of Kellogg. The mine is in what is locally known as the Silver Belt, so called because of the predominance of silver-bearing tetrahedrite in the ore from this area.

Previous Geologic Work in the Silver Belt.—Various aspects of the geology and mineralogy of the Silver Belt have been described by Ransome and Calkins (9), Umpleby and Jones (16), Rasor (10), Shenon and McConnel (13), Anderson (2), Willard (17a, 17b), Sorenson (14a, 14b, 14c), Thurlow and Wright (15), Robinson (11), Mitcham (8), and Kerr and Robinson (6). The most complete summary of the mineralogy is the paper by Mitcham.

SUMMARY OF REGIONAL GEOLOGY

The country rock of the Coeur d'Alene district consists of slightly metamorphosed sediments of the Precambrian Belt series that have been folded, faulted, and intruded by granitic stocks and dikes of various types. The Belt series in this area has been subdivided into six formations on the basis of lithology. No unconformities have been recognized. From bottom of the series to top, the formations are as follows: Prichard, Burke, Revett, St. Regis, Wallace, and Striped Peak. The total section is at least 23,000 feet thick. The Silver Summit mine is developed in the Revett, St. Regis, and Wallace formations.

The veins of the Silver Belt, as well as the veins in the rest of the district, generally strike between N 45° W and west, and generally dip steeply to the southwest. Many of the veins and faults of the district are in zones of rock that are bleached to a color lighter than normal, presumably by hydrothermal solutions that preceded the ore-forming solutions (13, 14a, 14b, 14c, 4, 8). The exact nature of the bleaching is now being studied; it appears to be significantly different from alteration halos described by Lovering (7) and Sales and Meyer (12). With the possible exception of the uranium deposits in the Silver Belt, which have been dated as Precambrian in age (5), the deposits can be dated only as younger than the granitic stocks, which are younger than the Belt series.

SUMMARY OF GEOLOGY OF THE SILVER SUMMIT MINE

The Silver Summit mine is in the steeply dipping normal and overturned beds of the north flank of the Big Creek anticline; except in locally disturbed areas beds have a uniform near-vertical dip. The Wallace, St. Regis, and Revett formations have been identified in the mine, but the ore shoots are confined to the St. Regis formation. Two major faults of the district, the Polaris and Silver Summit faults, and two faults of lesser magnitude, the Chester and Silver Summit vein faults, are present in the mine. The faults strike N 70° W to west in the mine area, with dips generally ranging from 60° to 75° S. They are all probably normal faults, except possibly the Silver Summit fault. The Polaris fault has a maximum displacement of about 5,000 feet (13).

The commercial-grade tetrahedrite ore found to date lies within a single 225- to 375-foot-wide bleached zone in the St. Regis formation. A series of ore shoots in siderite veins occupies approximately the center of the bleached zone, beginning on the east at the juncture of these siderite veins and the Silver Summit fault. These ore shoots trend generally N 70° to 80° W, diverging from the Silver Summit fault. They nearly parallel the beds in strike, but they dip 65° to 75° S. The siderite veins are in a zone of quartzitic beds and tend to narrow as they approach the thinner argillaceous beds to the south; even persistent siderite veins generally penetrate the argillaceous beds for only short distances.

An ore body normally is made up of one to several siderite-tetrahedrite veins occupying a system of tight fractures that may be minable for a width of 25 feet. Many small veins diverge into the footwall from the main vein system. The ore shoots are as much as 700 feet in stope length and up to 450 feet in pitch length; with only two exceptions, they are much greater in stope length than in pitch length. In this respect the ore shoots differ from most of the Coeur d'Alene district ore shoots, which mostly have pitch lengths several times greater than the stope lengths.

A number of post-mineral cross faults have been noted, but vein displacements range from only a few inches to a few feet. The amount of displacement along faults paralleling the veins has not been determined.

SUMMARY OF MINERALOGY OF THE TETRAHEDRITE VEINS

The mineralogy of the Silver Summit tetrahedrite veins appears to be simpler than the mineralogy of the Polaris and Sunshine mines (2, 17b). Minerals generally present in the Silver Summit veins are pyrite, siderite, ankerite, gersdorffite, tetrahedrite, chalcopyrite, and quartz, and they were introduced in approximately this order. A minor amount of quartz followed the siderite, but the main periods of introduction of quartz followed the emplacement of the sulphide minerals. This order contrasts with the main period of introduction of quartz in the Polaris vein, which is pre-sulphide, described by Willard (17b). Vugs in the quartz contain second-generation siderite, tetrahedrite, chalcopyrite, and a third generation of quartz crystals. This assemblage is accompanied in places by polybasite crystals. Barite has been

reported as occurring in some veins; galena is very scarce; one occurrence of pyrrhotite is known; and arsenopyrite is present in the wall rock but has not been recognized in polished specimens. Sphalerite, bournonite, boulangerite, and proustite, reported in other tetrahedrite veins of the Silver Belt (2, 17a), have not been recognized. The secondary cobalt minerals, erythrite ($Co_3As_2O_8 \cdot 8H_2O$) and bieberite ($CoSO_4 \cdot 7H_2O$), are both present, after oxidation, in the mine workings.

According to J. M. Axelrod of the U. S. Geological Survey, who made the X-ray identification, the lines of gersdorffite are doubled, and, therefore, there are probably two gersdorffites, the unit cells of which are about 1 percent different in length.

OCCURRENCE OF GERSDORFFITE

Gersdorffite is present, although generally in noncommercial quantities, in all of the tetrahedrite-bearing veins (minor as well as major), but in the Silver Summit mine there is a definite suggestion, based on the distribution of cobalt bloom, that greater amounts are concentrated at the edges of ore shoots, an observation confirmed by P. J. Shenon in other mines of the Silver Belt (oral communication). Much of the main cobalt-bearing ore shoot has been mined or is now inaccessible for detailed re-sampling, so that the quantitative distribution of cobalt and nickel in the ore shoot could not be determined. A study of polished surfaces shows that gersdorffite is replaced by tetrahedrite and, therefore, is older than the tetrahedrite. The few contacts of pyrite and gersdorffite seen were of the "mutual boundary" type, and no conclusions as to relative age could be made. Gersdorffite in siderite is subhedral to euhedral and there is no evidence for the age relationship between the gersdorffite and the siderite. It appears that gersdorffite was the first mineral introduced into the veins during what might be called the ore-shoot stage of mineralization, a conclusion supported by Willard (17b) and Mitcham (8), and that tetrahedrite replaced much of the gersdorffite.

The Silver Belt mines are warm (air temperatures in the high 80's) and moist, so that gersdorffite readily oxidizes in a few months, producing cobalt bloom. The veins cut in the Silver Summit mine now have some cobalt bloom scattered along exposed surfaces, so that it is obvious, even without assay information, that a cobalt-bearing mineral is a common minor constituent of even the smallest of the tetrahedrite-bearing veins. According to J. S. Vhay (oral communication), however, cobalt bloom may not appear if iron is abundant in the ore; iron arsenate will form instead of erythrite (cobalt arsenate) and the available cobalt will form the soluble cobalt sulphate, which may then rapidly be removed from mine workings by water. Thus the absence of cobalt bloom in old workings in the Silver Belt on veins that are known to contain abundant pyrite and arsenopyrite does not necessarily mean the absence of cobalt minerals.

Veins worthy of detailed sampling and assaying can most readily be identified using the α-nitroso β-naphthol test (3) whereby the presence of cobalt can be quickly and decisively determined. A quantitative technique using 2-nitroso-1-naphthol has been developed by the U. S. Geological Survey (1).

This technique would be very helpful in determining the parts of veins that should be assayed by conventional methods.

SEQUENCE OF FORMATION OF THE VEINS AND ORE SHOOTS

The veins were formed in disturbed areas along and adjacent to faults of relatively little displacement. The two major faults of the area (Polaris and Silver Summit) have apparently controlled the formation of the minor faults, but they were only slightly mineralized themselves. Ransome (9) first noted that the major faults in the Coeur d'Alene region were in general unmineralized, and the situation in the Silver Summit mine is merely another example. "Disturbed areas" is perhaps the best term to use, as in many places there is little evidence of shearing in the quartzite, merely shattering.

Pyrite was introduced into fractures and disseminated into the wall rock out from fractures. Minor movement along the fractures then sheared much of the pyrite, and in most, but significantly not all, of the areas siderite was then introduced. Fractures in pyrite and country rock were filled with siderite, and there was some minor replacement of pyrite by siderite.

Many small siderite veinlets are filled open fractures in quartzite, as shown by matching vein walls, but the larger siderite veins were formed by replacement of fragmented quartzite outward from the fractures. Such siderite veins reach 8 feet in width. Not all areas of fracturing were accessible to the siderite-forming solutions, as there are areas with tetrahedrite that contain almost no siderite. A minor amount of quartz was introduced after the siderite.

It is probable that gersdorffite was the first introduced of the ore-shoot stage sulphides.

Tetrahedrite entered the siderite along an intricate network, defined in part by siderite grain boundaries and in part by minor fractures, and then began to replace siderite out from the initial veinlets until bodies of massive tetrahedrite, up to 1½ feet wide, were formed. As noted above, tetrahedrite is not restricted to areas of siderite. Chalcopyrite and very minor quantities of galena were then introduced into the ore shoots.

After the main stage of ore deposition, large quantities of milky-white quartz partly replaced ore-shoot minerals as well as siderite and country rock. Some of this late quartz fills tension fractures that are perpendicular to the main veins, but most of the late quartz was introduced along shear planes paralleling the main veins. Vugs in the quartz are lined with quartz crystals that may reach 2 inches in length and half an inch in diameter. Much more rarely, in addition to quartz crystals, the vugs are lined with siderite rhombs on which are perched tetrahedrite, chalcopyrite, quartz, and polybasite crystals. Such vugs are present on the 3,000 level approximately 4,500 feet below the present ground surface. There is little doubt that the polybasite is primary.

CONCLUSIONS

1. Minor amounts of gersdorffite, (Ni,Co,Fe)AsS, are present in the tetrahedrite-siderite veins of the Silver Summit mine. One ore shoot is esti-

mated to have contained 0.40 percent cobalt and about 1.0 percent nickel, as well as copper and rich silver ores.

2. The greatest concentration of gersdorffite should be found along the edges of tetrahedrite ore shoots, although the central portions of shoots may contain gersdorffite.

3. The known occurrence of cobalt bloom or gersdorffite in other Silver Belt properties suggests that other ore shoots containing commercial quantities of cobalt and nickel may exist in the Silver Belt mines. Newly opened veins should be assayed for cobalt using 2-nitroso-1-naphthol test as a routine measure.

ACKNOWLEDGMENTS

The writers are grateful to the officials of the Hecla and Polaris Mining Companies for permission to publish this paper.

U. S. GEOLOGICAL SURVEY, SPOKANE, WASH.,
AND HECLA MINING CO., WALLACE, IDAHO,
Feb. 16, 1954

BIBLIOGRAPHY

1. Almond, Hy, 1952, A field method for the determination of traces of cobalt in soils: U. S. Geol. Survey Open File Report.
2. Anderson, R. J., 1940, Microscopic features of ore from the Sunshine mine: ECON. GEOL., vol. 35, no. 5, p. 659–667.
3. Feigl, Fritz, 1947, Qualitative analysis by spot tests, Elsevier Publishing Company, 3d ed., 574 p.
4. Hobbs, S. W., Wallace, R. E., and Griggs, A. B., 1950, Geology of the southern third of the Mullan and Pottsville quadrangles, Shoshone County, Idaho: U. S. Geol. Survey Open File Report.
5. Kerr, P. F., and Kulp, J. L., 1952, Pre-Cambrian uraninite, Sunshine mine, Idaho: Science, vol. 115, no. 2978, p. 86–88.
6. Kerr, Paul F., and Robinson, Raymond F., 1953, Uranium mineralization in the Sunshine mine: Mining Eng., vol. 5, no. 5, p. 495–511.
7. Lovering, T. S., 1949, Rock alteration as a guide to ore—East Tintic district, Utah: ECON. GEOL., Monograph 1, 65 p.
8. Mitcham, T. W., 1952, Indicator minerals, Coeur d'Alene silver belt: ECON. GEOL., vol. 47, no. 4, p. 414–450.
9. Ransome, F. L., and Calkins, F. C., 1908, Geology and ore deposits of the Coeur d'Alene district, Idaho: U. S. Geol. Survey Prof. Paper 62, 203 p.
10. Rasor, C. A., 1934, Silver mineralization in the Sunshine mine, Coeur d'Alene district, Idaho: Master's thesis, University of Idaho.
11. Robinson, Raymond F., 1950, Discussion of uraninite in the Coeur d'Alene district, Idaho: ECON. GEOL., vol. 45, no. 8, p. 818–819.
12. Sales, Reno H., and Meyer, Charles, 1949, Results from preliminary studies of vein formation at Butte, Montana: ECON. GEOL., vol. 44, no. 6, p. 465–484.
13. Shenon, P. J., and McConnel, R. H., 1939, The Silver Belt of the Coeur d'Alene district, Idaho: Idaho Bur. Mines and Geology Pamphlet 50, 8 p.
14. Sorenson, Robert E., (a) 1949, Deep discoveries intensify Coeur d'Alene activities: Eng. and Min. Jour., vol. 148, no. 10, p. 70–78. (b) 1948, Silver Summit opens rich ore: Eng. and Min. Jour., vol. 149, no. 7, p. 70–73. (c) 1951, Shallow expressions of Silver Belt ore shoots, Coeur d'Alene district, Idaho: Mining Eng., vol. 3, no. 6, p. 605–611.
15. Thurlow, Ernest E., and Wright, Robert J., 1950, Uraninite in the Coeur d'Alene district, Idaho: ECON. GEOL., vol. 45, no. 5, p. 395–404.
16. Umpleby, J. B., and Jones, E. L., Jr., 1923, Geology and ore deposits of Shoshone County, Idaho: U. S. Geol. Survey Bull. 732, 156 p.
17. Willard, Max E., (a) 1938, Mineralization at the Polaris mine: Master's thesis, University of Idaho. (b) 1941, Mineralization at the Polaris mine: ECON. GEOL., vol. 36, no. 5, p. 539–550.

PARAGENESIS OF THE ORES OF THE PALOMAS (HERMOSA) DISTRICT, SOUTHWESTERN NEW MEXICO[1]

HENRY L. JICHA, JR.

CONTENTS

	PAGE
Abstract	759
Introduction	760
Location	761
General geology	761
General relations of the ores	761
Mineralogy	765
General relations of the minerals	766
Gangue minerals	766
Quartz	766
Barite	766
Sulfide minerals	766
Silver minerals	770
Oxidized minerals	772
Iron and manganese oxides	772
Other minerals	773
Paragenesis	773
Formation of talc	775
Nature, age, and origin of the mineralizing solutions	776
Summary and conclusions	777

ABSTRACT

Low temperature lead-zinc-silver mineralization of Tertiary age characterizes the Palomas Mining District in the western part of Sierra County, in southwestern New Mexico. The ore occurs in fissure veins and replacement bodies in Paleozoic limestones and dolomitic limestones. Structural control of ore deposition has been exerted by fractures or shaly horizons. The principal hypogene minerals are galena, sphalerite, chalcopyrite, and argentite. Associated minerals are pyrite, polybasite, and tetrahedrite. The gangue consists mainly of talc, with associated calcite, quartz, barite, and clay minerals. Supergene minerals include covellite, native silver, limonite, carbonates of lead, zinc, and copper, silver halides, and a little vanadinite, descloizite, and pyromorphite.

Talc, which occurs both as vein filling and in wall-rock alteration, is thought to have been formed by the action of silica-bearing hypogene solutions. Little transportation appears to have taken place during the early stages of oxidation, as evidenced by the intimate association of hypogene and supergene silver minerals. The mineralization is believed to have been brought about by alkaline hydrothermal solutions whose origin is in

[1] Publication authorized by the Director, New Mexico Bureau of Mines and Mineral Resources.

doubt, but may be connected with the sources of Tertiary volcanic activity in the area. An unusual feature of the deposits is the occurrence of talc as the chief gangue mineral.

INTRODUCTION

In the summer of 1952 an examination and mapping project in the Palomas Mining District was begun by Dr. Richard H. Jahns and the author, under the auspices of the New Mexico Bureau of Mines and Mineral Resources. Pre-

Fig. 1. Index map of Sierra County, showing location of the Palomas Mining District (arrow).

vious work in the area was done by Gordon (2)[2] and Harley (8), but no detailed study of the geology and mineralogy was made. During the course of detailed mapping of the mines of the district, a suite of ore specimens was obtained for laboratory examination. The purpose of this paper is to present the data obtained in the laboratory examination of the ore specimens, together with some conclusions as to the origin and mode of emplacement of the deposits which were arrived at on the basis of these data.

Acknowledgments.—The author wishes to acknowledge the help and cooperation of Dr. Richard H. Jahns and Alfred Miesch in the search for mineral specimens suitable for study. Messrs. George Koepke and H. B. Jones, who were operating the Nana mine under lease, kindly provided ore specimens from that mine as mining progressed during the fall and winter of 1952.

Dr. Jahns kindly read the manuscript critically and offered many useful suggestions.

Location.—The Palomas Mining District is located on the eastern slope of the Black Range, in T. 13 S., R. 8 W., near Hermosa in Sierra County, New Mexico (Fig. 1) an area of many mining districts in earlier days.

GENERAL GEOLOGY

The Hermosa area, which includes the Palomas Mining District, is in the upthrown block of a north-south trending horst. In this upthrown block mainly Paleozoic sediments are exposed. The east fault separates the Paleozoic sediments from the Tertiary (?) Palomas gravels. The west fault is in Tertiary latitic volcanics, part of which have been preserved in the upthrown block. The main part of the Palomas district is located in a relatively small faulted domal structure in the Paleozoic rocks of the upthrown block exposed in Palomas Canyon.

The sedimentary formations exposed in the Palomas district include the Montoya, Valmont, Fusselman, Onate, Percha, Lake Valley, Kelly, Magdalena, and Abo formations. They range in age from Ordovician through Permian. The sediments are in places unconformably overlain by Tertiary latitic volcanics which include flows, flow breccias, and tuffs.

GENERAL RELATIONS OF THE ORES

The ores of the Palomas district occur principally as thin shoots, stringers, and pockets along subsidiary fractures of small displacements associated with the major faults in the domal uplift that is exposed in Palomas Canyon. Some mineralization was also observed at the intersections of minor fractures and of minor fractures and bedding-plane slips. The largest part of the mineralization occurs in Ordovician and Silurian dolomites and dolomitic limestones under the shaly base of the Devonian Onate formation. Locally small replacement bodies of ore occur in higher formations. In general, the ore bodies are small, yielding from a few to a few hundred tons of high-grade ore, and from two to ten times as much low-grade ore. At places the ores are vuggy; more

[2] Numbers in parentheses refer to References at end of paper.

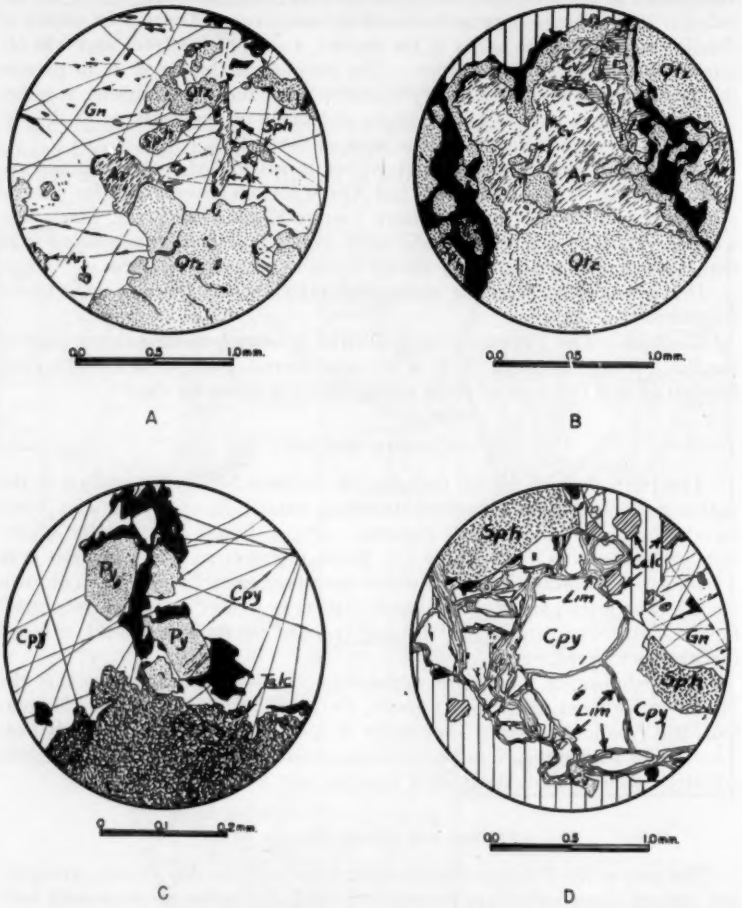


FIG. 2. Camera lucida drawings: A. Quartz (Qtz) and sphalerite (Sph) replaced by galena (Gn) and all replaced by argentite (Ar). Black areas are holes. B. Argentite (Ar) replaced quartz (Qtz) and is itself replaced by covellite (Cv). Black spaces are holes. Vertical ruling is mounting medium. C. Pyrite (Py) replaced by chalcopyrite (Cpy) and both replaced by talc. Black areas are holes. D. Chalcopyrite (Cpy) replaced by limonite (Lim) and covellite (Cv). Original texture shows chalcopyrite replaced sphalerite (Sph) and sphalerite replaced by galena. Some late calcite (Calc). Mounting medium (vertical ruling). Black areas are holes.

commonly they are fairly tight. The sulfide minerals are largely galena and sphalerite. Small amounts of chalcopyrite, pyrite, tetrahedrite, pyrargyrite, polybasite, and argentite are also present. Gangue minerals include calcite, quartz, barite, talc, and montmorillonite.

Wall-rock alteration is evidenced mainly by the formation of talc. Most of the high-grade ore bodies are surrounded by a "skin" of talc, commonly mixed with calcite. This "skin" ranges in thickness from ⅛-inch to 3 inches, and averages about ¾-inch. The talc "skin" commonly breaks free of the unaltered wall-rock. Talc is also commonly present in areas where pyrite is the only sulfide present. Relatively large volumes of talc, which varies in color from white through yellow to almost black, commonly accompany metallization

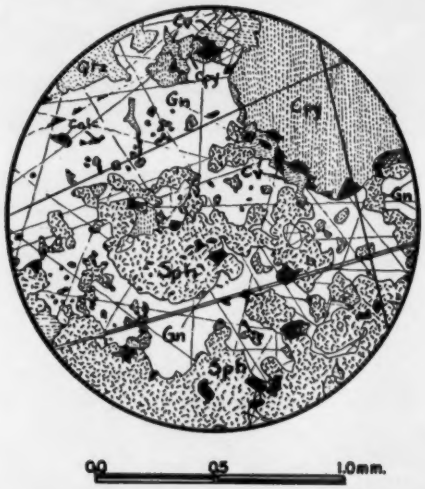


FIG. 3. Sphalerite (Sph) and quartz (Qtz) replaced by chalcopyrite (Cpy) and galena (Gn). Covellite (Cv) shows that some secondary sulfide enrichment has taken place. Late calcite (Calc) also present. Black areas are holes. Camera lucida drawing.

of all grades. "Skin" talc is yellowish or creamy white, with more or less iron stain. Fault and fracture openings also contain some talc, part of which is almost certainly replacement of the dolomitic gouge. Some of the dolomite and dolomitic limestone near ore shoots is replaced by talc, which is partly disseminated and also occurs as layers around blocks of unmineralized dolomite. These bands show Liesegang-like rings (Fig. 9) that apparently developed from the outside inward; the centers are unreplaced masses of original dolomite.

Large amounts of talc are good indications of nearby ore and with few exceptions talc is present where there are high-grade ores. However, talc is also widespread as a minor constituent where ore is sparse or not present.

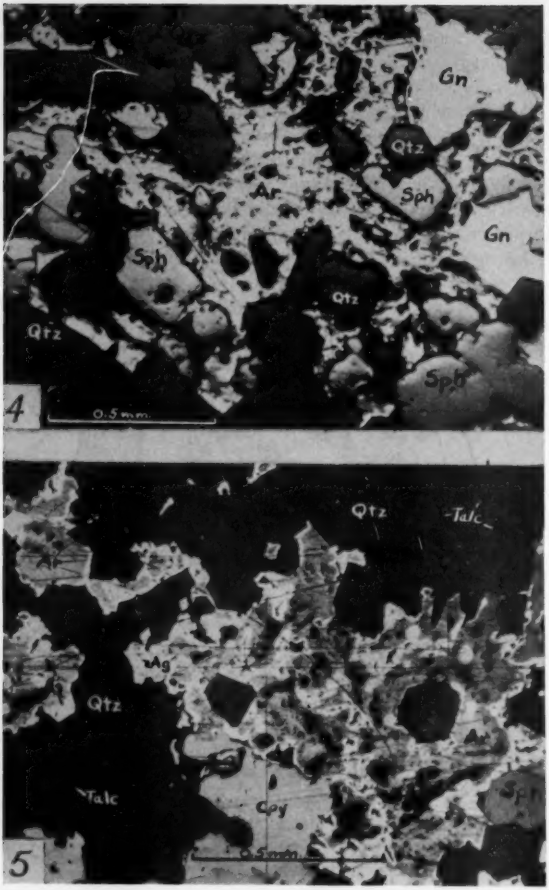


FIG. 4. Vug in crystalline quartz (Qtz) filled with sphalerite (Sph), galena (Gn), and argentite (Ar).

FIG. 5. Vug in crystalline quartz (Qtz) with sphalerite (Sph), chalcopyrite (Cpy), argentite (Ar), and native silver (Ag). Note that silver has replaced argentite peripherally and from holes. This texture is similar to that described by Bastin (1925, p. 54) for pearcite replaced by native siler at Aspen, Colo.

Some silicification has also occurred. At many places silica partly replaces the dolomitic limestone country rock in association with talc. Less commonly, large masses of quartz form fine-grained crystalline aggregates to the complete exclusion of the country rock. Vugs in these aggregates commonly contain some metallic minerals.

At many places the ores are accompanied by crystalline calcite in rhombs as much as 2 inches on an edge. The calcite is generally closely associated with talc and also fills the openings along many of the larger pre-mineralization faults. Where calcite occurs along bedding-plane slips, it commonly forms the locus of deposition for sulfides.

Many of the high-grade ore deposits occur in the form of nodules or "pillows," up to 18 inches in length and breadth, and 8 inches thick, that are completely, or almost completely surrounded by talc in the form of a "skin" described previously. The ore also occurs as fracture fillings and partial replacements accompanied by relatively large volumes of talc. The replacement bodies and fissure-fillings may be of equally high-grade and contain the same minerals as the ore pillows but they are generally surrounded by lower-grade, disseminated ores. The disseminated ores commonly consist of nodules of sulfides, scattered through relatively large masses of talc.

The high-grade ores consist largely of galena and sphalerite with chalcopyrite, argentite, and silver sulfo-salts. The galena, sphalerite, and chalcopyrite are commonly coarse-grained, in crystals as much as 2 cm in diameter. The silver minerals are finer-grained, and generally occur only as small masses scattered throughout the ore. The lower-grade ores rarely contain recognizable silver minerals.

The hypogene ores of the Palomas district have been subjected to extensive supergene alteration, chiefly oxidation, mainly in areas where faulting and solution have opened the primary ores to the ingress of meteoric waters. Surface exposures are, of course, highly altered. Generally, a high degree of oxidation is characteristic only of those portions of the ore deposits exposed to weathering, but some oxidation occurs on almost all levels of the mines. Oxidation in the lower levels is probably due to through-going fractures and faults that appear also to have been channels for the hypogene solutions. A high degree of oxidation is common near fractures that adjoin and parallel the Pelican fault in the Day mine. Many similar localities could be cited.

Small-scale sulfide enrichment is found in most of the ores. In the rich ores, native silver occurs associated with argentite, covellite, and chalcocite. Oxidized ores are commonly of the dry-bone type, being made up largely of lead and zinc carbonates. At some localities copper carbonates, brochantite, cuprite, and limonite are accessories. In one area, the ores are largely lead and zinc carbonate in a boxwork structure, accompanied by vanadinite, descloizite, mimetite, pyromorphite, wulfenite, and some quartz. The accessory minerals form crystal sheafs and crusts on the cerrusite boxwork.

MINERALOGY

Thirty-eight mineral species have been identified during the present investigation. Five species which were not found in the present suite have been reported to occur (14). Of the thirty-eight minerals identified, fifteen have not been previously reported. A list of the mineral species of the Palomas district is given in Table 1.

GENERAL RELATIONS OF THE MINERALS

Gangue Minerals.—Calcite occurs in three forms: (1), As large milky white rhombs commonly closely associated with talc, which in some places localizes sulfides, mainly sphalerite and galena, and also is found along barren fault planes. (2) Similar calcite occurs with some of the sphalerite in contact with the earlier calcite, or as growths on the earlier calcite and sphalerite; sphalerite occurs only on the earlier calcite whereas galena occurs on both. (3) Clear calcite occurring as vug and fracture fillings in the ores with a complex crystal form of rhombs modified by scalenohedrons, and commonly associated with yellow or black talc; the fourth variety similar to the third, but is clouded with specks of limonite.

TABLE 1

MINERALS OF THE PALOMAS DISTRICT

*Anglesite	$PbCO_3$	Gypsum	$CaSO_4 \cdot 2H_2O$
*Argentite	Ag_2S	Hematite	Fe_2O_3
*Azurite	$Cu_3(CO_3)_2(OH)_2$	Lepidocrocite	$FeO(OH)$
Barite	$BaSO_4$	*Limonite	Hydrated ferric oxides
*Bornite	Cu_5FeS_4	*Malachite	$Cu_2CO_3(OH)_2$
Brochantite (?)	$Cu_4SO_4(OH)_6$	Manganite	$MnO(OH)$
†*Bromyrite	$AgBr$	†*Marcasite	FeS_2
*Calcite	$CaCO_3$	†*Miargyrite	$Ag_2Sb_2S_4$
†*Cerargyrite	$AgCl$	Mimetite	$Pb_5(AsO_4, PO_4)_3Cl$
*Cerussite	$PbCO_3$	Polybasite	$Ag_{16}Sb_2S_{11}$
*Chalcocite	Cu_2S	*Pyrargyrite	Ag_3SbS_3
Chrysocolla	$CuSiO_3 \cdot 2H_2O$	*Pyrite	FeS_2
*Chalcopyrite	$CuFeS_2$	Pyromorphite	$Pb_5(PO_4, AsO_4)_3Cl$
*Covellite	CuS	*Quartz	SiO_2
Cuprite (rare)	CuO	*Silver	Ag
Descloizite	$(Pb, Zn, Cu)_2(OH)VO_4$	*Smithsonite	$ZnCO_3$
†*Embolite	$Ag(Cl, Br)$	*Sphalerite	Zns
Epsomite	$MgSO_4 \cdot 7H_2O$	*Talc	$Mg_3(Si_2O_5)_2(OH)_2$
*Galena	PbS	*Tetrahedrite	$5Cu_2S \cdot 2(Cu, Fe)S \cdot 2Sb_2S_3$
*Gold	Au	Vanadinite	$Pb_5Cl(VO_4)_3$
Goethite	$HFeO_2$	*Wulfenite	$PbMoO_4$

* indicates that mineral has been previously reported as occurring in the Palomas district.

†* indicates that mineral has been mentioned as occurring in the Palomas district but is not found in the present suite.

(?) indicates that the identification of this mineral is in doubt.

Quartz occurs in the ores in three forms: (1) as vuggy, crystalline aggregates which commonly contain small but valuable amounts of sulfides (Figs. 4, 5) both as complete fillings and as thin coatings on the quartz crystals; the contained sulfides include sphalerite, tetrahedrite, galena, and argentite, and talc. Some botryoidal quartz occurs as veinlets in sphalerite, and a third form occurs exclusively with the secondary ores, as vugs and crystalline crusts in and on such minerals as cerussite, vanadinite, and pyromorphite; many of the crystals are clouded with specks of limonite.

Barite occurring as yellowish translucent tabular crystals from 1 to 2 cm long is a common constituent of oxidized ores and is also found in association with pyrargyrite and polybasite, which form crystal incrustations on it.

Sulfide Minerals.—Pyrite is rare. It occurs with talc or in association with chalcopyrite, which commonly completely surrounds it. *Marcasite* has

been reported to occur in the ores as incrustations on galena (14, p. 209), but was not seen in the ores examined.

Sphalerite is generally present in the high-grade sulfide ores in lesser quantity than galena. It is light to dark amber in color, and occurs as discrete crystals with dodecahedral form and as crystalline crusts. On weathered sur-

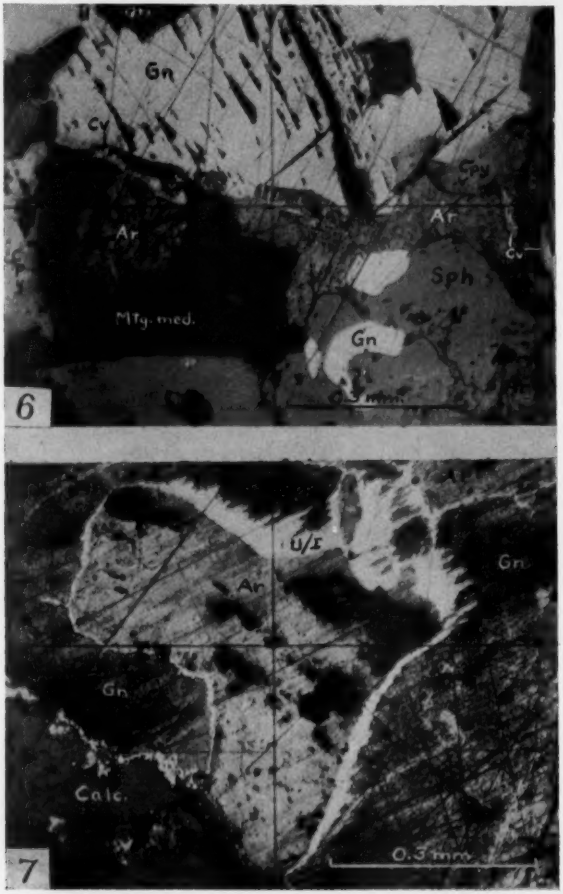


FIG. 6. Galena (Gn) and argentite (Ar) replaced sphalerite (Sph), quartz (Qtz) and chalcopyrite (Cpy). Light streaks in argentite are covellite (Cv). Flat gray is mounting medium (Mtg. Med.).

FIG. 7. Argentite (Ar) in galena (Gn) etched dark with hydrogen peroxide to show border of unidentified mineral (U/I) in galena around argentite. Calcite (Calc) at lower left.

faces the crystals are generally dark gray with a submetallic luster, and appear to have been slightly oxidized. Under the microscope it is seen to contain numerous inclusions of chalcopyrite, with some tetrahedrite and galena. The more important relations are embayment and veining of sphalerite, which also occupies cleavages in the calcite; sphalerite also occurs as crusts on vuggy quartz.

Tetrahedrite occurs sparsely in the ores, mainly as small blebs and masses in sphalerite to the exclusion of all other minerals. It is most abundant in the ores of the Palomas Chief mine, and is associated with sphalerite or with argentite, being embayed by the latter.

Chalcopyrite and bornite are not quantitatively important. Chalcopyrite is common in the high-grade silver ores of the district, and is generally regarded as an indication of silver. In polished sections it is seen as tiny rods and blebs in sphalerite, along cleavages or peripheral. Some blebs lead into veinlets of chalcopyrite in the same plane of weakness. In partly oxidized ores, the chalcopyrite is partly replaced by covellite and chalcocite, and limonite is a common associate (Fig. 2D). The chalcopyrite is embayed by galena and argentite, and it in turn embays galena. Some bornite is associated with chalcopyrite.

Galena is quantitatively the chief sulfide mineral. It occurs mostly as cubes modified by octahedrons, and as dodecahedrons. Some anhedral galena appears to have inherited its shape from pre-existing minerals. Some fine-grained "steel" galena occurs at bends in fractures that cut across the ore bodies; near such fractures some galena has curved cleavages as much as 40 degrees from the normal trend of the cleavage line.

A specimen of galena from the Nana mine was analyzed spectrographically. No bismuth or antimony were found. The limits of detection of these elements were five parts per million and two hundred parts per million, respectively. The lack of antimony in the galena is particularly interesting in view of the presence of small amounts of antimony minerals (tetrahedrite and polybasite) in the ores. Silver is present in this particular galena to the extent of 0.1 percent. It has been shown (17, p. 305) that galena can contain this much silver without giving visible evidence of the silver content, even on etching with hydrogen peroxide. Etching on a polished surface of the sample has shown that the silver is present in a non-etching mineral tentatively identified as a lead-silver sulfide that occurs as veinlets in and peripheral coatings on galena. This mineral has been described by Bastin and Laney (1, p. 21–23) and also by Petersen (16, p. 493).

Traces of Fe, Mg, Ti, Al, Mn, and Cu were also found. Of these elements, Wasserstein (22) has found that Fe, Ti, and Mn may substitute in very small amounts for Pb in the galena lattice. Other elements listed by him are Sn, Cd, Sr, and V, none of which have been found to occur in this galena. The presence of Mg, Al, and Cu may be ascribed to minor contamination of the sample.

Harley (8, p. 94) has described cubes of supergene galena in cavities, but the author has found no evidence of supergene galena.

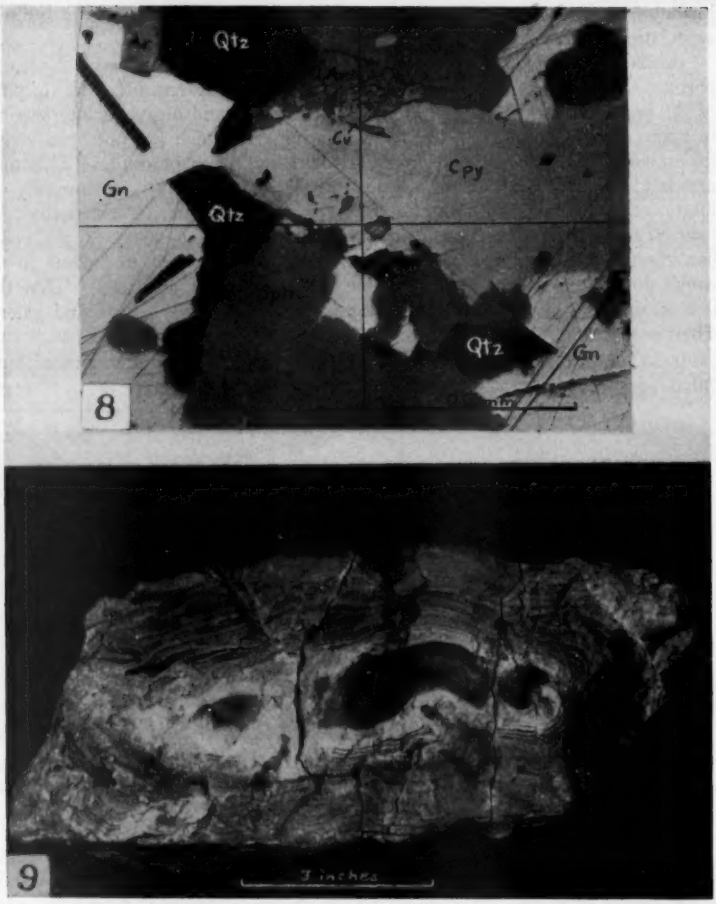


FIG. 8. Sphalerite (Sph) replaced quartz (Qtz), chalcopyrite (Cpy) replaced sphalerite and quartz; galena (Gn) replaced sphalerite, quartz, and chalcopyrite; argentite (Ar) replaced all previous minerals, and covellite (Cv) replaced argentite.

FIG. 9. Dolomite (dark gray, center) replaced by talc which shows Liesegang-like rings. Dolomite is replaced from outside of block inward.

Covellite and chalcocite are both found in the ores of the Palomas District. Covellite occurs as small microscopic veinlets and as bladed masses, and as rims around chalcopyrite, or as veinlets in argentite. In the more highly enriched ores covellite generally is present to the exclusion of most or all of the argentite. Chalcocite is scattered through the enriched portions of the ores

in somewhat larger amounts than covellite. For the most part it is in intimate association with covellite.

An *undetermined mineral* is indicated by etching galena with hydrogen peroxide, which in places brings out a minor, but persistent difference in parts of the crystals. In the silver-poor ores, cleavages and cleavage intersections in many crystals show rims and blebs of a mineral which has not been identified specifically, but which does not etch with hydrogen peroxide. This mineral is identical in all other properties to galena, except that it commonly exhibits some resistance to the action of nitric acid but after a short period, not over 30 seconds, it etches in a manner similar to galena. Bastin (1, p. 21–23) has described this same mineral, which occurs at Tonopah, and came to the conclusion that it is probably a double sulfide of silver and lead. That this is a strong possibility is shown in the relations between argentite and galena. The rims of this intermediate mineral are much wider in the vicinity of such contacts than where little or no argentite is found. No mineral other than galena shows rims and veinlets of the undetermined mineral.

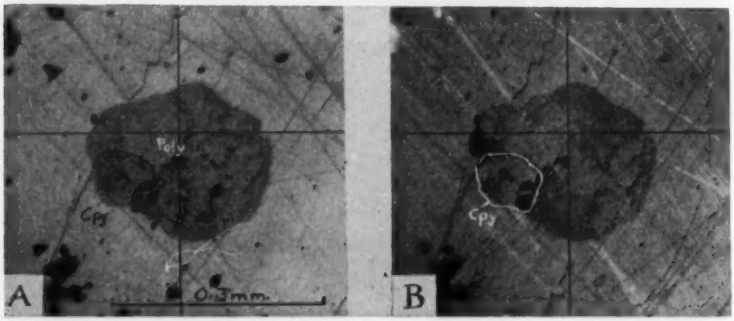


FIG. 10. A. Polybasite (Poly) and chalcopyrite (Cpy) in galena. B. Same as A, crossed nicols. Note anisotropism of polybasite, which shows crystal to be twinned.

Silver Minerals.—Polybasite is rare, having been found only in a few specimens of rich ore from the Nana mine where it occurs as small blebs and veinlets in galena (Fig. 10). It cuts across the galena cleavages in places; in other places it follows the cleavages. In one specimen small crystals of polybasite occur on barite. Microscopic examination shows the mineral to be green-gray, somewhat lighter than argentite and slightly darker and greener than tetrahedrite, with a hardness of C −. It is strongly anisotropic, the colors being yellowish-green, grayish-purple, and brown (Fig. 10). Though no discernible internal reflection has been found, the optical properties and etch tests agree with those given for polybasite (20, p. 126a).

Pyrargyrite is seen in the richer ores as small irregular grains commonly associated with and embaying chalcopyrite, blue-gray, slightly harder than galena, and anisotropic in shades of gray. The mineral reacts to etch tests

in a manner which suggests that it is pyrargyrite (20, p. 127). However, its identification is tentative. Some hand specimens contain crystals identified as pyrargyrite in association with polybasite on barite.

Miargyrite was reported from the Palomas district by Jones (10, p. 343), but none was found in the ores examined.

Argentite occurs sparsely throughout the richer ores as small blebs, veinlets, and thin films in sphalerite and galena, commonly along the cleavage. Chalcopyrite and tetrahedrite are also found as associates of argentite, which usually embays rather than forms veinlets in these minerals. The contact between argentite and galena characteristically shows rims of a mineral which is thought to be a double sulfide of lead and silver. In one specimen, argentite

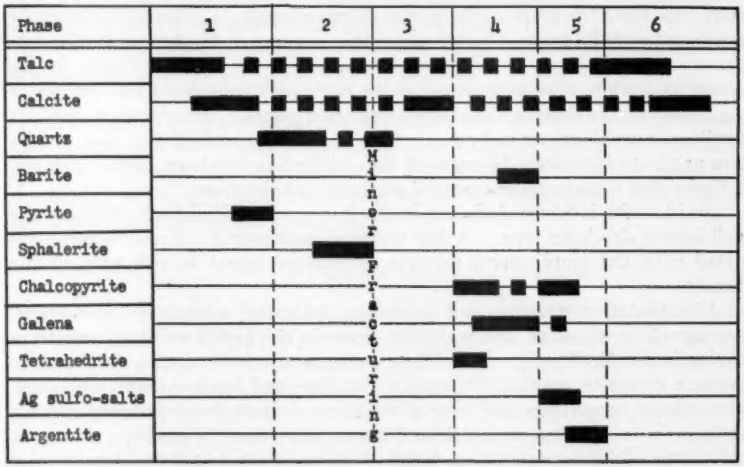


FIG. 11. Paragenetic sequence of the hypogene ores.

occurs as aggregates of small crystals that show twinning. Such argentite is reported to have formed at temperature above 179° C (17, p. 317). Argentite occurs in vugs in some places, in association with native silver (Fig. 5). Similar occurrences have been reported from the Comstock lode (2, p. 53). Another common associate of argentite is covellite, which embays or forms veinlets in argentite. In a few areas the argentite forms rims around masses of covellite.

Native silver is rather rare and is found only in the more highly enriched of the argentite-bearing sulfide-talc ores, where it occurs as flakes, wires and small arborescent masses associated with argentite, as well as in tiny blebs and veinlets in and around argentite (Fig. 5) or covellite; in places it is in small isolated masses in talc.

Silver halides, notably cerargyrite, embolite, and bromyrite, have been reported from the Palomas district (8, p. 94), but the author was unable to find any, probably because the high-grade oxidized ores of silver were stoped out at an early date.

The ratio of silver to gold is several thousand to one; the gold content is minute, but some free gold has been reported in the oxidized ores by Harley (8, p. 94).

Oxidized minerals.—Malachite and *azurite* are found as films, stains, and crusts on most oxidized ores that contained copper sulfides; cuprite and chrysocolla are also present and brochantite has been identified tentatively. Most of these minerals are found in association with cerussite, smithsonite, and limonite, and in some of the dry-bone ores.

Cerussite and *limonite* are the most common products of oxidation. Cerussite generally occurs as aggregates of small crystals that may form a box work indicating the shape of the parent galena crystals. Cerussite is commonly associated with limonite, which forms a thin coating on the boxwork of cerussite crystals. It is one of the main constituents of the oxidized ores. It also occurs as a white coating on some of the more highly oxidized sulfide ores of the Nana mine, and on oxidized ores from other mines. The cerussite contains small amounts of copper and zinc. *Anglesite* is only rarely found as an oxidation product of galena. In some of the oxidized ores where sulfides remain, it forms thin films on galena crystal surfaces and cleavages.

Smithsonite is fairly abundant in the low-grade oxidized ore, forming the well-known dry-bone type. A few crusts of smithsonite are also found associated with the more varied mineral assemblage found in one area in the district.

Phosphates, vanadates, and arsenates, including vanadinite, descloizite, pyromorphite, mimetite, and wulfenite, occur in the highly oxidized ores from a mine in the Wolford group. These minerals are associated with the more common cerussite, smithsonite, calcite, limonite, and basic copper carbonates. The ores are very vuggy and some of the minerals have developed into crystals as large as 1 cm in length and 1 to 2 mm in diameter. *Vanadinite* occurs in two closely allied forms: (1) as large (1 cm by 2 mm) well-terminated prismatic crystals of deep orange-brown color, and (2) as tiny bunches of straw-yellow acicular crystals. *Descloizite* (probably cuprodescloizite) occurs as bunches of tiny yellow acicular crystals, difficult to distinguish from vanadinite of similar form except by chemical tests, and more commonly as a crust of shiny, black, acicular crystals on limonite-cerussite boxwork. Microchemical tests indicate the presence of copper. *Pyromorphite* occurs as white to almost colorless, subtransparent to translucent crystals about 1 cm long in association with descloizite, cerussite, limonite, and quartz. *Mimetite* occurs as small greenish prisms in association with pyromorphite. *Wulfenite* occurs in small amounts as incrustations in fractures associated with the more highly oxidized ores.

Iron and Manganese Oxides. Limonite is one of the most common constituents of oxidation. It is generally orange-brown to yellow-brown and subcrystalline to earthy. In polished section it can easily be seen to be made up

of lepidocrocite and goethite. In the less-oxidized ores, limonite shows a layered growth and the minerals alternate. They are distinguished from each other under the microscope by the fact that lepidocrocite is lighter in color and has a bright red internal reflection as compared to the darker colored goethite, which has a brown internal reflection. Both show pleochroism, but lepidocrocite is more highly pleochroic. The distinction is made easily only when both minerals are present. In hand specimen, with low-power magnification, lepidocrocite is found to form red, translucent botryoidal crusts associated with brown, less well-crystallized goethite.

Hematite is found in some parts of the district as a fine red powder coating bedding surfaces in mineralized areas.

Small bunches of dark brown spots and tiny dark brown nodules occur in association with limonite in many of the oxidized ores have been found to contain manganese. The mineral represented is thought to be manganite, from its physical properties and association with limonite.

Other Minerals.—Gypsum occurs as vug fillings in many of the harder ores that have been subjected to supergene alteration. It also occurs in some of the softer, talcy ores as discrete crystals and aggregates. Gypsum is also found in large porous masses of fibrous crystals in some of the moderately oxidized portions of the deposits. *Epsomite* occurs in some of the mine workings which are now dry but were once filled with water. *Kaolinite* is present in the gangue of the ores where supergene action has taken place. Its common association is with the talc masses around the ores.

PARAGENESIS

With the exception of some argentite and all covellite and chalcocite, all of the sulfide minerals are considered to be hypogene. In addition, the gangue minerals talc, barite, calcite, and quartz are also hypogene, though the last two also occur as supergene minerals.

The primary mineralization sequence in the Palomas district is shown in Figure 11. Much of the faulting antedates the mineralization but most of the mineralized fault zones show evidence of post-mineralization movement. The mineralization proper occurred with little apparent discontinuity, but has been divided into several phases for convenience in reference and description.

The first phase was marked by the formation of white talc and large rhombs of milky white calcite. This was followed by the deposition of small amounts of pyrite. In the second phase crystalline quartz was formed. Sphalerite was introduced slightly later. Minor fracturing took place at the end of this phase. In the third phase of mineralization minor botryoidal quartz and some additional milky calcite were added. The calcite of this phase commonly occurs as secondary growths on calcite rhombs of the first phase. The fourth phase consists largely of sulfide minerals. Tetrahedrite and chalcopyrite were deposited contemporaneously, closely followed by galena and small amounts of barite. Galena was contemporaneous with a large part of the chalcopyrite. Phase five is marked by the introduction of sulfosalts of silver, mainly polybasite; these were followed by argentite, the last hypogene sulfide deposited.

Some chalcopyrite is thought to have accompanied the silver minerals. The closing phase of the mineralization is a second talc and calcite phase. However, the calcite of this phase is clear and is in the form of rhombs modified by scalenohedron faces. The talc is pale yellow to cream-colored and waxy. It forms late veinlets in the sulfides and at some places also forms large envelopes around the sulfides.

The above generalized sequence does not appear to have been followed exactly throughout the district, though the exceptions are mainly matters of degree. Some of the ores are poor in silver and contain few visible silver minerals. In such ores the late carbonate and talc phase is also poorly represented. This may indicate blocking of the late hypogene solutions from the ores by fracture-filling. The presence of silver minerals and chalcopyrite is thought to indicate comparatively greater permeability of the ores that contain large amounts of these minerals to the late hypogene solutions. The hypogene ores that contain large amounts of argentite and chalcopyrite are generally vuggy or else they are enclosed in masses of a fairly porous talc. Where the ores are "tight" there is not much argentite and chalcopyrite. At other places the carbonate and quartz of phase three are not prominent.

Talc appears to have been formed throughout most of the period of mineralization, and hence its formation was contemporaneous with the sulfide deposition. The contemporaneity of the talc formation with sulfide deposition in the ore "pillows" is almost unquestionable, as indicated by the almost constant association of the talc with the sulfides and the mutual consistency of the variation in the size of the sulfide masses and their associated talc deposits. Though talc formed throughout the mineralization sequence, the two major epochs of talc formation are recognized because talc was one of the chief minerals formed in those parts of the mineralization sequence.

Chalcopyrite is all later than sphalerite in the paragenetic sequence, in spite of some relations that might indicate unmixing. The general irregularity of distribution of the inclusions of chalcopyrite in sphalerite, and their accompaniment by veinlets and other encroaching grains of chalcopyrite is evidence for this conclusion.

Argentite is considered to be mostly hypogene. It encroaches on most minerals of the primary sequence in a manner that suggests hypogene replacement, coupled with the presence of some argentite that must have formed over 179° C. In addition, supergene minerals are found to encroach upon and form veinlets in most argentite. Some argentite is thought to be supergene, as it forms encroaching rims on supergene covellite. No detailed paragenetic sequence has been established for the supergene ores. The location of most of the ores above the present water table favors oxidation over sulfide enrichment, and indeed, oxidation is the most prominent form of supergene activity. Sulfide enrichment has gone on in these ores only on a much smaller scale. This fact points to a rapid lowering of the water table and subsequent exposure of the ores to oxidation, probably resulting from the rapid downcutting of Palomas Creek. However, small bodies of perched water exist, and the percolation of meteoric waters in other areas is extremely restricted. The perched water and lack of easy access of meteoric waters to oxygen may account for a large

part of the supergene sulfide deposition. That sulfide enrichment may occur as part of an incomplete oxidation process has been brought out by Lindgren (12, p. 164). Where ore occurs below water level, sulfide enrichment is undoubtedly also going on.

A rough summary of supergene alteration might be as follows: The early stages of alteration are marked by the formation of covellite, chalcocite, native silver, and some limonite. Galena may have cleavage films of anglesite. In later stages, when oxidation predominated, sphalerite was dissolved and some smithsonite formed. Cerussite, gypsum, limonite, and copper carbonates were formed as well as minor wulfenite. Some relict galena generally remained. Silver halides were formed. In the most advanced stages of alteration, minerals such as hematite, vanadinite, descloizite, pyromorphite, mimetite, chrysocolla, brochantite, and cuprite were formed on cerussite, smithsonite, and limonite. Most of the silver was leached out. This synthesis follows closely the evidence provided by known localities of occurrence of the various types of ore mentioned.

FORMATION OF TALC

The problem of the origin of the talc associated with the Palomas ores has been studied in some detail.

Insoluble residue studies have shown the content of insolubles in unaltered dolomites and dolomitic limestones of the Palomas district to be relatively minor. The general figures for the lower Paleozoic formations are between 3 and 9 percent by weight, excluding chert of chert nodules. Differential thermal studies of these residues show that their clay content is small. There were some indications of the presence of illite and possibly montmorillonite. X-ray studies tend to confirm these indications.

The formation of talc is thought to have resulted from the introduction of hot alkaline siliceous solutions into the dolomitic country rock and may have taken place as follows:

$$4SiO_2 + H_2O + 6(Ca, Mg)CO_3 \rightarrow Mg_3(Si_2O_5)_2(OH)_2 + 3CaCO_3 + 3CO_2$$

This same process is thought to have taken place during the formation of talc deposits in dolomitic limestones and marbles (5; 11, p. 434). As talc occurs in large amounts only where the country rock is highly dolomitic and is found only sparingly in deposits associated with the Mississippian and Pennsylvanian rocks, which are dominantly high-calcium limestones, such an hypothesis seems probable. Shaly layers that have been altered in part to talc also contain a high proportion of dolomite in their unaltered state. Some of the "hypogene" calcite is thought to be a by-product of the formation of talc from the magnesia in the dolomites and dolomitic limestones. The almost constant association of talc with unaltered primary sulfides is an important factor in the assumption that the talc is hypogene in origin. Ross and Hendricks (19, p. 71) indicate that talc may be formed under hydrothermal conditions at temperatures of about 350° C in alkaline environments. The experiments of Bowen and Tuttle (4) corroborate these indications.

Part of the silica for the formation of talc and for deposition of free quartz may have been derived from chert in the dolomites and dolomitic limestones under and surrounding the ore deposits. Evidence for this tentative conclusion is found in the fact that at many places in the mineralized areas the cherts of the Montoya formation are largely replaced by calcite. It is thought probable that this replacement was accomplished by hypogene solutions. The silica thus liberated may have taken part in the formation of talc.

The presence of kaolinite in some samples of partly oxidized ore may be attributed to the action of supergene sulfate waters (18, p. 174). Kaolinite generally forms in acid environments (19, p. 23) which are incompatible with the alkaline environment necessary for the formation of talc.

An analysis of a specimen of slightly oxidized ore is given in Table 2. Recalculation of the figures to mol fractions and development of the possible

TABLE 2

ANALYSIS OF SLIGHTLY OXIDIZED ORE FROM THE NANA MINE, PALOMAS DISTRICT

Constituent	Percent	Probable minerals*	
Ag	1.84	Argentite	—Ag_2S
Cu	3.29	Native silver	—Ag
Pb	52.89	Chalcopyrite	—$CuFeS_2$
Fe	1.85	Covellite	—CuS
Zn	0.82	Galena	—PbS
S	10.17	Sphalerite	—ZnS
		Cerussite	—$PbCO_3$
SiO_2	20.37	Anglesite (?)	—$PbSO_4$
TiO_2	0.13	Quartz	—SiO_2
Al_2O_3	1.22	Kaolinite	—$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$
CaO	0.00	Talc	—$Mg_3Si_4O_{10}(OH)_2$
MgO	4.19	Manganite	—MnO(OH)
MnO	0.47	Goethite	—$HFeO_2$
P_2O_5	0.00	Leipdocrocite	—FeO(OH)
SO_4	0.03		
CO_2	0.97		
H_2O	2.33		
Total	99.53		

* All of these minerals with the exception of kaolinite, manganite, and anglesite have been identified in polished sections of this specimen. The clay mineral was identified by X-ray diffraction methods. Assays show that this specimen contains some gold.

Analysis by H. B. Wiik.

mineral content by a process similar to the development of the norm of an igneous rock indicates that there should be talc and some kaolinite in the ore as well as free quartz. The presence of talc and kaolinite has been confirmed by X-ray diffraction patterns.

NATURE, AGE, AND ORIGIN OF THE MINERALIZING SOLUTIONS

The mineralization is thought to have been accomplished by moderate- to low-temperature alkaline solutions. As has been previously stated, the formation of talc by introduction of silica into magnesian limestones requires alkaline conditions. Inasmuch as talc was formed throughout the mineralization

sequence, alkaline conditions probably prevailed throughout the entire period of mineralization. The low-temperature nature of the deposit is evidenced in the mineral suite as well as the general restriction of the deposits to fissure fillings with only minor replacement. It should be noted that the low-temperature mineralization in the Palomas district is in direct contrast to the high-temperature silicate mineralization found in the Cuchillo Mountains to the north and east of Winston (9).

The age of the mineralization is mid-Tertiary (probably Miocene). Mineralized and altered dikes similar in composition to the late Tertiary latitic volcanics in the surrounding region occur in the district. The mineralized zone also extends into some of the volcanics that overlap the sediments in one of the mineralized areas. The source of the mineralizing solutions has not been definitely established, but may be related to the igneous activity that took place in the region in late Tertiary time. There is no conclusive evidence of intrusives other than a few mineralized latitic dikes in the area.

Assuming that conditions have not changed markedly since the beginning of the major epoch of supergene enrichment, the following characteristics of supergene solutions are postulated. The supergene solutions were probably restricted in their flow. The present rate of circulation is very low. This low rate of circulation suggests poor access to oxygen. The waters were also probably not very acid, as suggested by the carbonate gangue. Formation of such minerals as covellite, chalcocite, native silver, and argentite under supergene conditions suggests that where such alteration occurs the solutions contained copper sulfate, silver sulfate, and ferrous sulfate. In an oxygen-poor environment, little ferric sulfate would be formed. Where ferric sulfate was formed by reduction of silver sulfate to silver, hydrolysis would yield an acid solution, which on contact with the carbonate wall rock should yield ferric hydroxide, gypsum or epsomite, and carbon dioxide. Limonite, gypsum, and epsomite have all been found in areas of such supergene alteration. Similar occurrences have been described by Bastin (2, p. 96–97). Most of the equations for these reactions have been given by Emmons (6).

SUMMARY AND CONCLUSIONS

The ore deposits of the Palomas district are examples of low-temperature lead-zinc-silver mineralization in Paleozoic limestones and dolomitic limestones. The main hypogene sulfides are galena, sphalerite, chalcopyrite, and argentite, with some pyrite, tetrahedrite, and polybasite. The gangue includes calcite, quartz, talc, and montmorillonite. An unusual feature of this deposit is the predominance of talc in the gangue and well-rock alteration. The talc is thought to have been formed by the action of siliceous solutions on the dolomitic wall-rock. Supergene action in the district has yielded a typical suite of oxidation products of lead, copper, iron, zinc, and silver sulfides, including limonite, cerussite, smithsonite, copper carbonates, silver halides, and also such minerals as vanadinite, descloizite, mimetite, pyromorphite, and wulfenite. Small scale sulfide enrichment is evidenced by the presence of covellite and chalcocite. The mineralization was probably introduced by hydrothermal

solutions of alkaline nature, as evidenced by the presence of talc and montmorillonite in the gangue. The mineralization is late Tertiary in age. The source of the hydrothermal solutions is in doubt, but may have been associated with the source of volcanic activity in the area.

NEW MEXICO BUREAU OF MINES
AND MINERAL RESOURCES,
SOCORRO, NEW MEX.,
March 11, 1954

REFERENCES

1. Bastin, E. S., and Laney, F. B., 1918, The genesis of the ores at Tonopah, Nevada: U. S. Geol. Survey Prof. Paper 104.
2. Bastin, E. S., 1923, Bonanza ores of the Comstock Lode, Virginia City, Nevada: U. S. Geol. Survey Bull. 735, p. 41–63.
3. ——, 1925, Silver ores of Aspen, Colorado: U. S. Geol. Survey Bull. 750, p. 41–62.
4. Bowen, N. L., and Tuttle, O. F., 1949, The system MgO—SiO_2—H_2O: Geol. Soc. Am. Bull., vol. 60, p. 439–460.
5. Burfoot, J. D., 1930, Talc and soapstone deposits of Virginia: ECON. GEOL., vol. 25, p. 805–826.
6. Emmons, W. H., 1917, The enrichment of ore deposits: U. S. Geol. Survey Bull. 625.
7. Guild, F. N., 1917, A microscopic study of the silver ores and their associated minerals: ECON. GEOL., vol. 12, p. 297–353.
8. Harley, G. T., 1934, Geology and ore deposits of Sierra County,, New Mexico: N. Mex. School Mines, State Bur. Mines and Min. Res., Bull. 10, p. 90–98.
9. Jahns, R. H., 1944, Beryllium and tungsten deposits of the Iron Mountain District, Sierra and Socorro counties, New Mexico: U. S. Geol. Survey Bull. 945-C.
10. Jones, F. A., 1904, New Mexico Mines and Minerals, The New Mexican Printing Co., Santa Fe.
11. Keith, Arthur, 1903, Talc deposits of North Carolina: U. S. Geol Survey Bull. 213.
12. Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., 1910. The ore deposits of New Mexico: U. S. Geol. Survey Prof. Paper 68, p. 16, 62–67, 77, 267–268.
13. Lindgren, Waldemar, and Loughlin, G. F., 1919, Geology and ore deposits of the Tintic Mining District, Utah: U. S. Geol. Survey Prof. Paper 107.
14. Northrup, S. A., 1944, Minerals of New Mexico, Univ. N. Mex. Press, Albuquerque.
15. Palache, Charles, Berman, Harry, and Frondel, Clifford, 1944, Dana's System of Mineralogy, vol. I, John Wiley and Sons, Inc., New York.
16. Petersen, V. E., 1942, A study of the geology and ore deposits of the Ashbrook Silver Mining District, Utah: ECON. GEOL., vol. 37, p. 466–502.
17. Ramdohr, Paul, 1950, Die Erzmineralien und ihre Verwachsungen, Akademie Verlag, Berlin.
18. Ross, C. P., and Kerr, P. F., 1931, The kaolin minerals: U. S. Geol. Survey Prof. Paper 165, p. 151–176.
19. Ross, C. P., and Hendricks, S. B., 1945, Minerals of the montmorillonite group, their origin and relation to soils and clays: U. S. Geol. Survey Prof. Paper 205-B.
20. Short, M. N., 1940, Microscopic determination of the ore minerals: U. S. Geol. Survey Bull. 914.
21. Stuckey, J. L., 1937, Talc deposits of North Carolina: ECON. GEOL., vol. 32, p. 1009–1018.
22. Wasserstein, B., 1951, Precision lattice measurements of galena: Am. Mineralogist, vol. 36, p. 102–115.

SCIENTIFIC COMMUNICATIONS

THE USE OF AERIAL PHOTOGRAPHS FOR THE GRADUATE THESIS

ARTHUR W. RUFF

In the past graduate students in geology have had little opportunity to use aerial photographs as an aid in mapping areas they wish to study. The main objection has been the high cost of having the area photographed. In many instances interesting areas have not been studied because topographic maps were not available. During a student's limited time to study an area he should be occupied in collecting and classifying rocks, working out the stratigraphy, determining the structure, mapping, and in general studying problems in geology. The thesis problem should not necessitate spending one half the time in the field preparing a base map upon which to map the geology, and have only the remaining half of the time to study the geology.

Topographic maps have been commonly used for the base map very successfully in many areas, but the speed and accuracy of geologic mapping can be greatly increased by the use of aerial photographs in conjunction with topographic maps. If no topographic maps are available, aerial photographs may not only be used to map on but also as a base from which to construct a topographic map.

Common sources of aerial photographs of the United States are the U. S. Department of Agriculture, U. S. Soil Conservation Service, U. S. Forest Service, and private aerial survey companies. Usually these photographs are of too small a scale for satisfactory results in mapping the geology of small thesis areas. However, in work of a more regional character, such as recording the facies change of a formation that outcrops for many miles, these small scale photographs can be used to advantage. But for mapping an area of three or four square miles photographs should be used that have a scale of about 500 or 600 feet to the inch.

With more small companies doing aerial photographic work, the cost of having a small area photographed has dropped considerably. It is possible for a student to talk to a representative of the company and arrange for them to fly the area sometime when they are photographing another area in the vicinity. To keep the cost down the student should allow enough time so that no special flight by the company is needed. In this way it is possible to have an area photographed for 15 to 20 dollars a square mile. Naturally, if the area to be studied is very inaccessible and distant from any other areas being photographed, the cost of photographing will be much higher. The aerial survey company benefits by helping a graduate student to obtain aerial photo-

graphs for his graduate work, because then the graduate student will more likely use aerial photographs in later work. Many times people that have property in the area will share in the expense of having the area flown for copies of the photographs, or of the completed thesis. The company supplying the photographs should guarantee that the photographs will have sufficient overlap and sidelap so that the area is completely covered stereographically and that the amount of tilt is not objectional. The overlap should be at least 60 percent and the sidelap at least 30 percent, with not over three degrees of tilt.

Before an area is flown the student should mark the extremities of the area so that the pilot of the airplane will have no difficulty in locating the area. A good method of marking an area is to make a cross inclosed in a circle by pouring ordinary slaked lime on the ground. A 15-foot diameter circle can be picked out easily on photographs with a scale of 500 or 600 feet to the inch. If the photographs are to be used to construct a topographic map, control elevation points should be chosen, which if not identifiable from the air should be marked with lime. In geologic mapping an aneroid barometer is usually accurate enough for elevation control. It is possible to make a contour map from aerial photographs with only one or two elevation control points per square mile, but the accuracy of the final map is increased if more control points are used. It has been recommended by Nowicki [1] that a minimum of nine control points be used per photograph. More control points are needed in rough terrain. An accurate base line distance and direction must be identifiable on the photograph. A section line is very good for this if the corners are marked on the ground beforehand or in some way may be identified on the photographs. Since section lines are not exactly the same length or same direction, the true measured distance should be sought and taken from the survey notes. The time of day and year when the aerial photographs are taken is important particularly if the terrain has strong relief. If an area with strong relief is photographed when there are strong shadows these shadows can completely obliterate ground detail.

There are two common methods of mapping geology with aerial photographs which are: to map directly on the photographs, or to place a transparent material such as a piece of frosted celluloid over the photographs and map on the covering material. The author believes that mapping directly on the photographs is the better method. The disadvantages of the overlay method are that there may be loss of accuracy in the mapping because of slight movement of the transfer material as the mapping progresses, and ground detail is somewhat diffused through the transfer material, particularly on poor photographs. Also, to carry in the field photographs with overlays is more inconvenient than to carry photographs with no overlays. The advantages of using an overlay are that the photographs are not injured and subsequent stereoscopic use is not impaired, and it is easier to write on the overlay material than directly on the photographs. However, if the photographs are injured, extra prints may be made which are quite inexpensive and the stereoscopic work may

[1] Nowicki, A. L., 1944, Practical applications of the stereocomparagraph, Manual of Photogrammetry: Am. Soc. Photogrammetry, Pitman Pub. Corp., New York, p. 469–470.

be done on them. If the mapping is done directly on the photographs a matte finish is most desirable. But photographs with a semi-gloss finish may be used if sharper detail is required. A 4H pencil can be used on both the matte and semi-gloss finish.

It is convenient to use symbols and colors to designate rock formations on aerial photographs since there is little room to write long names or descriptions. A number should be written on the photograph where detailed notes are needed. The notes should then be recorded in a field note book indexed with this same number. After each day's mapping in the field the notes written on the photograph should be inked. This is very important because a day's field work may become blurred and completely useless if this practice is not followed. There is a much clearer conception of the overall geologic picture if the formations or rock types are colored on the photographs as the work proceeds. A hand stereoscope may be used in the field to view the photographs. But if the photographs are studied thoroughly in the office before going into the field there is little need of a stereoscope in the field.

In many areas terrestrial features have been produced by the differential erosion of geological structures. A geologist who is using aerial photographs on which to map finds that he has a much clearer picture of the terrain and thereby the geology than when using only topographic maps. In a sedimentary area geologic formations may sometimes be traced on photographs with ease. Then the field work can be used as a check and to furnish the more detailed geologic notes.

The first task in constructing a map from aerial photographs is to make a radial line plot of the area mapped. An excellent description of the radial line plot method is given by Smith.[2] This is a method of assembling aerial photographs so that the transfer of the ground detail on the photographs will be in true location on the finished map.

After the radial line plot is completed, the culture, drainage, and geologic notes are transferred to the base map by use of direct transfer, a camera lucida, or a vertical sketchmaster. Transfer by the direct transfer method is described by Davis and Foote.[3] Of these three methods the use of the vertical sketchmaster is the best and most accurate because it compensates for slight distortion in the photographs. The vertical sketchmaster is an instrument of the camera lucida type. By adjustment of the three leveling screws the photographic image seen on the base map may be varied so that all the reference points on the photograph coincide with the points on the radial line plot even if there is distortion caused by tilt in the photograph. If the radial line plot is constructed to a predetermined scale, the image from the vertical sketchmaster may be enlarged or diminished to this scale in one operation. In a map made from aerial photographs the system of drainage is very accurate even if reproduced by an inexperienced person.

There are many methods of using aerial photographs to prepare a topo-

[2] Smith, H. T., 1943, Aerial photographs and their applications, Appleton-Century-Crofts, Inc., New York, p. 161–173.

[3] Davis, R. E. and Foote, F. S., 1940, Surveying theory and practice, McGraw-Hill Book Co., Inc., New York, p. 852–855.

graphic map. The Multiplex Aero-pojector is used where more accuracy is desired and large areas are contoured. This method is usually much too expensive for student geologists.

To contour small areas with a minimum of equipment and expense the author recommends the floating line method. This method is described by Desjardins.[4] All that is needed to contour with this method are photographs with stereoscopic coverage of the area, a stereoscope, two small pieces of transparent celluloid, and time. The main disadvantage to this method is that a little time is needed to learn to operate the floating lines. However, after a little experience, contours can be drawn quite rapidly. This method is least accurate where the contours are widely spaced but is accurate enough for a geologic thesis.

The work of contouring the photographs should, if possible, be done in advance or in coordination with the field work. In this way the contours may be checked in the field and may be resketched more accurately if needed. Also, if possible, transfer of the notes to the base map should progress simultaneously with the field mapping. In this manner any facts that are omitted are usually apparent, and a check of the geology in question can be made before the work has progressed away from that area. It is advisable in some thesis areas to make a plane table map with a larger scale of a small part of the main area to show more detail in the geologic map. An example is where the surface detail geology of the area around a mine is mapped. This does not detract but adds to the value of aerial photographs for thesis mapping because the use of aerial photographs speeds mapping of the geology of the large area. Therefore, the student has more time to map the geology in detail in areas that are of interest or to spend more time on other geologic problems in the area.

CANANEA CONSOLIDATED COPPER CO.,
CANANEA, SONORA, MEXICO,
March 2, 1954

[4] Desjardins, L., 1950, Techniques in photogeology: Am. Assoc. Petroleum Geologists Bull. no. 12, vol. 34, Dec.

DISCUSSION

GEOLOGY OF AUSTRALIAN ORE DEPOSITS
BROKEN HILL

Contained in the valuable symposium "Geology of Australian Ore Deposits" published in 1953 by the Australasian Institute of Mining and Metallurgy in conjunction with the Fifth Empire Mining and Metallurgical Congress is a series of papers on Broken Hill that I would like to call to the attention of geologists who have not seen them.

"Mineralogy of the Broken Hill Lode" by F. L. Stillwell details in itemized form the many oxidized minerals, secondary sulphide minerals, and primary ore and gangue minerals composing the ores. The paper is factual in its treatment, contains little of a theoretical or controversial nature, and does not persuade the reader to adopt any theory or point of view.

Six other papers, "North Broken Hill Mine" by Q. J. Henderson, "Broken Hill South Mine" by A. B. Black, and "The Zinc Corporation and New Broken Consolidated Mines" by E. S. O'Driscoll, "The Consolidated Mine" by Haddon F. King, "The Pinnacles Mine and Its Environment" and "The Thakaringa Mine," also by King, are straightforward, brief descriptions of the mines. Except for some provocative sentences in the article by King on "The Pinnacles Mine and Its Environment," the authors have avoided the contentious subject of ore genesis and touch only lightly on matters of stratigraphy and structural interpretation where differences of opinion exist.

Very different is "The Geology of the Broken Hill District" by Haddon F. King and B. P. Thomson and its companion piece "The Broken Hill Lode" by King and E. S. O'Driscoll. The first of these is a major contribution to the regional geology of the Broken Hill district. It presents the results of the only comprehensive geologic study since the classic work of E. C. Andrews and his associates in 1919–22 [1] embracing detailed mapping of the greater Broken Hill district, which is some 80 by 30 miles in extent. The mapping and geologic interpretation by King and his associates takes its place with the best of an increasing number of great regional pre-Cambrian studies carried out in recent years by mining companies on other continents. Reduced and summarized on a map of 2 miles to an inch, much of the recorded intricate structure detail that I have seen on the larger scale maps is lost in presentation, but it is still impressive.

The present paper goes far beyond a mere description of rocks and structures and their portrayal on a map. It critically reappraises the stratigraphic succession, states conclusion regarding the origin of rocks about

[1] The Central Geologic Survey by contrast confined its detailed three-dimensional study to the immediate environment of the principal mines, a block 3 miles by 10 miles in area.

which there has been previous difference of opinion, reanalyses the structural features of the district, and presents some radically new views on ore genesis, lode emplacement, and the sequence of geologic events. Some of these will be subjects of controversy, I predict, for generations of geologists to come.

By and large, Andrews, were he still alive, would be gratified to see how much of his original geologic interpretation has survived this intensive scrutiny. As a member of the Central Geological Survey of 1936–39, I am pleased to see how many of the seeming heresies we advanced with slightly self-conscious boldness concerning stratigraphy and structure in the mines are now basic in the thinking of the geologists responsible for the newest study. It is also stimulating to see where new information and new thinking have modified some of the concepts we felt most secure in.

The stratigraphy has been generally confirmed, and major structures have been verified if somewhat modified. Some of the "granite sills" of previous surveys are now regarded, in part and perhaps in entirety, as granitized sediments. Post-metamorphism and post-lode granite and pegmatite are described for the first time. The "shocker" in the King-Thomson article is the proposition (a) that the ore is *not* hydrothermal in origin and (b) that it occurred as a simple conformable lead-zinc deposit before the region was folded and granitized. The authors state, "Thus the present ore deposits are thought of as having evolved from an earlier more simple form and as having acquired their present complex character during and as a result of the regional granitization, folding, and metamorphism. . . . The origin of the primitive deposits remains wholly conjectural." The "strong stratigraphic influence in the distribution of the original ore constituents" is thought to have consisted in part "of local syngenetic deposits of lime and manganese."

King and Thomson, like the rest of us, had trouble in understanding any mechanism by which vast quantities of dilute solutions can penetrate and selectively replace for a distance of miles two or more closely adjacent favorable rocks each with a characteristic and distinguishing aggregate of sulphides and gangue minerals (although they find no difficulty in accepting region-wide selective granitization). The members of the Central Geological Survey, like our predecessors, nevertheless accepted selective hydrothermal replacement,[2] however poorly understood, as being the only acceptable mechanism for ore emplacement consistent with their experience and understanding of metasomatic deposits elsewhere. King and Thomson apparently now believe acceptance of some undesignated, non-hydrothermal source of lead, zinc, silver, sulphur, and other elements poses fewer problems than hydrothermal replacement. I think many geologists will conclude with me that still greater problems arise when an attempt is made to identify this source as something other than hydrothermal. In throwing out a genetic relationship

[2] Burrell of the Central Geological Survey inclined to the belief that the diagnostic gangue minerals were dynamically metamorphosed sedimentary constituents whereas Garretty and I, while admitting that possibility, felt the evidence for hydrothermal quartz, rhodonite, and calcite was more compelling. See "Geology of the Broken Hill Ore Deposit, Broken Hill, N.S.W., Australia," by J. K. Gustafson, H. C. Burrell, and M. D. Garretty, Bull. Geol. Soc. Amer., vol. 61, pp. 1369–1437, 1950.

between the typical green feldspar "lode pegmatite," and lead-zinc ore with which it is spatially related the authors imply that the green color was imparted selectively during metamorphism to the feldspar of only those pegmatites close to ore whereas the feldspars of pegmatites distant from ore remained unpigmented. Ramdohr in an article quoted by the authors advanced the opinion that the ores were epithermal replacements which have been metamorphosed, so the authors are not alone in regarding the ores as pre-folding in age. I find it difficult to consider the lodes as pre-folding in age because the ore and gangue minerals are not deformed. They replace banded and gneissic rocks and therefore locally exhibit inherited banding. To consider them pre-folding, it is necessary to postulate *complete* subsequent recrystallization under conditions of virtually no stress.

Theories as to genesis of the Broken Hill ores now range virtually the entire spectrum of ore-forming mechanisms from the igneous, or almost igneous, of Andrews through the hypothermal of Lindgren and the Central Geological Survey, to the metamorphosed epithermal of Ramdohr, to the unnamed but apparently metamorphosed syngenetic or supergene of King and Thomson. The ores are dated anywhere from pre-folding, pre-metamorphism to post-folding and post-metamorphism.

The other paper, "The Broken Hill Lode" by King and O'Driscoll is something of an anticlimax after reading the "Geology of the Broken Hill District" because the startling new conclusions have already been anticipated. The detailed stratigraphy and structure of the mine area as here presented depart only slightly from the stratigraphy and structure presented at greater length by the earlier Central Geological Survey paper. An alternative to the Central Geological Survey method of tagging and keeping track of minor wrinkles is advanced which, according to the authors, avoids much of the difficulty (and, according to me, also much of the benefit) of the axial-plane method. Several sentences suggest that the authors misinterpreted the use to which the axial-plane method was put by the Central Geological Survey and the interpretation that was made of the results. For example, in speaking of the new method (the italics are mine) they state, "This recognition that the axial planes of the major and minor folds are not reconcilable (implicitly reached in 1939) made it possible to regard the overall (Western) anticline as a single persistent structure from New Broken Hill Consolidated Ltd. to the outcrop in the center of the field and probably to the North Mine. *This structure is shown in pl. I of Gustafson et al. (1950) as* WAO_2." In other words, the Central Geological Survey demonstrated it to be a single "structure"! What worries the authors is apparent in the next sentence. "On larger scale plans and sections this structure was interpreted as occupying a succession of axial planes from west to east going south." A virtue of the axial-plane method is that it can be applied on any scale. In the first instance cited we ignored the minor flutings on the large structure, whereas we analysed the minor flutings in the large-scale plans and sections. This is a minor quibble, and it is clear from a comparison of cross-sections in the Central Geological Survey paper and the present paper that the present authors were in very substantial agreement with the Central Geological Survey even as to minor details of structure. I say *were* in agreement ad-

visedly. Haddon King last December wrote me describing a deep drill hole intersection of banded iron formation and Footwall Gneiss at the Zinc Corporation-New Broken Hill Consolidated boundary in the footwall of the lead lode where no one anticipated finding these rocks. It is now possible that we have all been mistaken both in the sequence of ore horizons between the Footwall Gneiss and Hanging Wall Gneiss and in the nature of the ore folds (i.e., they may be considerably more complex than previously thought). It may require many months of new underground development to strengthen or weaken this suspicion. In the meantime, as King writes, "some elements of the Broken Hill structural concept have gone back to the melting pot, and it will be some time before they crystallize out again."

Broken Hill is still a challenge. It is also a severe testing ground for geological techniques and theories. It is fortunate that geological work there is being vigorously pursued by such capable and independently thinking geologists.

J. K. GUSTAFSON

1300 LEADER BUILDING,
CLEVELAND 14, OHIO,
June 8, 1954

SOME CONSIDERATIONS REGARDING LIQUID INCLUSIONS AS GEOLOGIC THERMOMETERS

Sir: Recently, in the above paper, Skinner (ECON. GEOL., vol. 48, no. 7, 1953, p. 541–550) has challenged one of the basic assumptions of inclusion thermometry: that the amount of liquid in fluid inclusions has remained constant since entrapment, permanently recording the PTX conditions of the vein-forming solutions. His data indicate that high pressure differentials between the inclusion fluids and host crystal media drive liquid in or out of fluid inclusion cavities in quartz. In his discussion, Skinner supports Kennedy's suggestions,[1] that primary fluid inclusions occur along lineages and that liquid is capable of movement along the lineage boundaries.

Although his experimental work appears very straightforward, from the work done on fluid inclusions in quartz at the U. S. Geological Survey laboratories we have been inclined to doubt that a significant amount of liquid could work its way out of, or into, primary fluid inclusions in the time of the runs, under the conditions given. We have heated many plates of quartz from various localities, thinner than the one Skinner used, to temperatures as high as or higher than the filling temperature to which he heated his and observed no change in the filling temperature on cooling and reheating, except for inclusions that obviously lost part or all of their liquid through fractures.

Recently we repeated, in part, Skinner's experiment using synthetic quartz grown by the Brush Laboratories Company. The fluid inclusions contained in this quartz are two-phase (liquid and vapor) at room temperature and form a thin veil in the new growth on both sides of the seed plate. The degree

[1] Kennedy, G. C., 1950, ECON. GEOL., vol. 45, no. 6, p. 533–547.

of filling is essentially constant for all inclusions. Temperatures of formation calculated from observed filling temperatures and pressures during growth agree within 1 percent, in degrees Centigrade, of the actual formation temperature. The inclusions are undoubtedly primary. Quartz plates were studied on a microscope heating stage,[2] without removal of either plate or thermocouple junction during the entire cycle of heating, cooling, and reheating. Measured temperatures are reproducible within 3° C.

From the results of the experiment, shown in Table I, it is evident that liquid under high internal pressures did not migrate from the inclusions, other than along fractures, during heating runs up to 6 hours. Runs of longer dura-

TABLE I.

EFFECT OF HIGH INTERNAL PRESSURES ON THE STABILITY OF FLUID INCLUSIONS IN SYNTHETIC QUARTZ.

Inclusion	Temperature of filling before heating, ° C	Temperature of run, ° C	Approximate* internal pressure, bars	Duration of run, hours	Temperature of filling after heating, ° C
1	320				320
2	320				320
3	320				320
4	322	340	290	3	322
5	320				320
6	322				322
7	317				315
1	320				320
2	320				320
3	320				320
4	322	345	325	6	322
5	320				320
6	322				322
7	315				Leaked
1	320				
2	320				
3	320				
4	322	350	Violent decrepitation beginning at approximately 349° C.		
5	320				
6	322				

* Derived from the PVT relations of pure water, assuming negligible volume change.

tion were not attempted, as most if not all leakage observed by Skinner occurred during 3-hour runs. The effect of high external pressures, which Skinner shows will cause liquid to migrate into the inclusion cavity, has not yet been investigated in our laboratory, but inasmuch as we have not been able to force liquid out, it seems improbable that liquid can be added to primary fluid inclusions.

Investigations of the stability of fluid inclusions in calcite support the results given above. Leakage was not observed in inclusions in various calcites

[2] Described by Richter, D. H., and Abell, J. F., 1953, Am. Mineralogist, vol. 38, p. 1269–1271.

even when the filling temperatures were exceeded by 70° C, for periods up to 6 hours.

It is our contention therefore that the results of Skinner's experiments are not generally applicable and that it is entirely possible that the single crystal of quartz he used is exceptional in some of its properties. The number, size, and distribution of the inclusions in the plate that he used indicate that it was

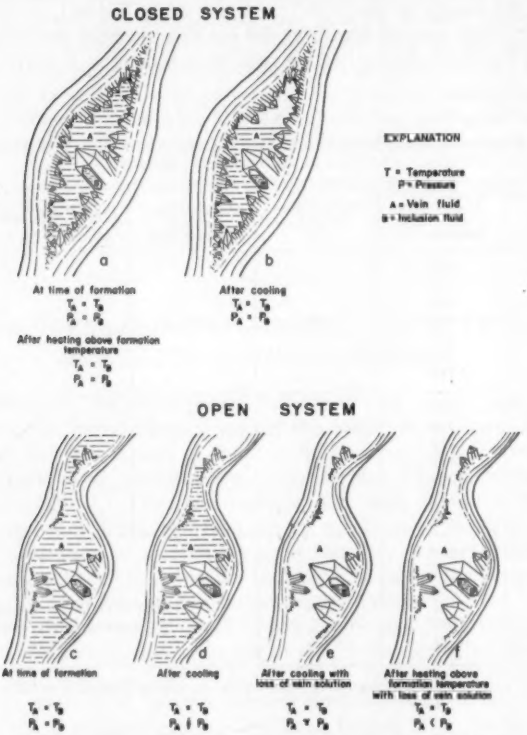


FIG. 1. Diagrams illustrating the pressure relation between inclusion fluids and host crystal media at time of formation, after cooling, and upon reheating, in both a closed and open system.

cut from near the base of a crystal, where veils are very numerous. In this part of a crystal there is always the possibility that fractures, fissures, and other irregularities would allow migration of fluids that would not be possible in the clear part of the crystal.

There is at least one other difficulty in making a general application to leakage in quartz and other minerals. In driving water in or out of the inclu-

sions, Skinner used differential pressures of hundreds of atmospheres. How are those differences produced in nature? The diagrams in Figure 1 illustrate the pressure relations between the liquid in a hypothetical inclusion and host crystal media on cooling and reheating, in both a closed and an open system.

In a closed system the crystal after formation is still bathed in the solution from which it grew (Fig. 1a). As the system cools, or is reheated above the original formation temperature, the pressure in the inclusions and outside of the crystal must be essentially the same (Fig. 1b, 1a).

The relations in an open system, on the other hand, are slightly different. Although pressure equilibrium is maintained during formation and shortly thereafter (Fig. 1c), further cooling will produce a small pressure differential owing to the difference in vapor pressure of the inclusion fluid and hydrostatic pressure of the vein solution (Figure 1d). If after, or during cooling the vein solutions contract or are lost, small vapor pressure differentials may or may not exist, depending on the composition of the remaining vein fluid (Fig. 1e). It is conceivable, of course, that a later solution can come in under a much higher hydrostatic pressure than did the original one, or that a relatively dry intrusion can heat up the quartz (or other mineral) without enough water, or solution, present to maintain equilibrium pressure on the crystals (Fig. 1f).

These two latter conditions would be analogous to Skinner's experiments, but evidence favoring interpretations such as these is lacking. Likewise, it is difficult to find a natural situation applicable to Kennedy's postulation [3] of the maintenance of high hydrostatic pressure on a crystal during cooling. A hydrostatic pressure of 500 bars would require a completely connected column of water nearly 3 miles high; conditions comparable to this, although not impossible, are certainly not a general rule. Furthermore, the fact that the vugs remain open indicates the rocks have not collapsed to put pressure on the crystals; therefore, the solution in the vugs would not be subjected to the pressure of all the overlying rocks, but would contract on cooling, just as the liquid in the individual inclusion does.

To summarize, we think that before Skinner's interpretation is too generally accepted, his experiments should be repeated with quartz from various localities, from several kinds of crystals, and from different parts of a crystal that grades from milky to clear. If they all give essentially the same results, then it will be necessary in each study to attempt to outline a more detailed history of the crystals since they were formed to see whether they have been subjected to post-formation conditions that could have changed the degree of filling.

DONALD H. RICHTER
EARL INGERSON

U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D. C.,
June 10, 1954

[3] Kennedy, G. C., op. cit.

LAND-SURFACE SUBSIDENCE AND ITS RELATION TO THE WITHDRAWAL OF GROUND WATER IN THE HOUSTON-GALVESTON REGION, TEXAS

Sir: The authors (A. G. Winslow and W. W. Doyel) of this admirable report on land-surface subsidence in the region lying between Houston and Galveston on the Gulf Coast of Texas, show conclusively by the results of successive nets of level lines of first-order precision that the land-surface has subsided over the area studied by as much as 2.6 feet, maximum. They show also that the subsided area coincides with an area from beneath which large volumes of ground water have been removed over the past ten years, and that the subsidence has been progressive over the period of water removal. They attribute the subsidence to the withdrawal of the ground water and they suggest that "the withdrawal of large quantities of ground water probably caused the compaction of the clays and, to a much smaller degree, of the sands and, consequently, the land-surface subsidence."

In support of this suggestion, the authors cite Meinzer's findings [1] that compression, resulting from reduction of hydraulic pressures in aquifers, occurs largely in the finer-grained rocks. As water is withdrawn, the hydrostatic pressure in the sands is reduced and a pressure difference is established between the clays and the sands, causing water to move from the clays into the sands.

Applying Meinzer's principle to the Houston-Galveston region, the authors explain:

> As the artesian pressure in the sands is lowered by pumping, a hydraulic gradient is established between the sands and the adjacent clay beds. As a result, the water is drained from the clays and the artesian pressure which helps to support the weight of the overlying material is decreased, causing the clays, which are less competent than the sands, to be compacted.

Because the persuasive application of this general principle by the authors to their specific experience will be of particular interest to a number of geologists, it seems worthwhile to point out that the same explanation was put forward to account for a similar land-surface subsidence in the Houston-Galveston area, many years ago.

In 1926, Pratt and Johnson [2] described local subsidence in the Goose Creek Oil Field, centrally located between Houston and Goose Creek. At Goose Creek the surface subsided as much as 3.2 feet, maximum, over an area of several square miles, during a period of about 10 years. The present authors refer to the paper describing the subsidence at Goose Creek, stating that it ascribes the subsidence "principally to the withdrawal of oil and gas," and remarking that "it seems reasonable to attribute part of the subsidence to the withdrawal of ground water."

[1] Meinzer, O. E., and Wenzel, L. K., 1942, Occurrence, origin and discharge of ground water: Chapter X in Hydrology: Natural Research Council, Physics of the Earth, Vol. 9, McGraw-Hill Book Co., Inc., New York, N. Y., p. 458.

[2] Pratt, Wallace E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek oil field: Jour. Geology, vol. 34, p. 577–590.

Actually, the paper describing the subsidence at Goose Creek states the opinion that "the cause of the subsidence is to be found in the extensive extraction of oil, water, gas and sand from beneath the affected area." This conclusion is supported by observations that emphasize the importance as factors contributing to subsidence, of reduction of hydrostatic pressures in the sand reservoirs, and of the draining of water into the depleted oil sands from the clays or gumbos with which the sands are interbedded and the consequent shrinkage and compaction of these clays.

It is explained that the geologic section in this locality consists largely of poorly consolidated clays, the water content of which is high—as much as 30 percent by weight. The void space left in the sands by the removal of oil and gas is reoccupied "by water draining more slowly from the adjacent clays; and it is a well known fact that the draining of clays causes them to become more compact. This, in turn, would permit subsidence of the overlying surface."

At the date of the subsidence of the land surface at Goose Creek this theory that subsidence of this character resulted in part from the drying and resultant compaction of the clays with which the oil sands are interbedded, by reason of the escape of original water content of the clays into the depleted oil sands—found little acceptance among petroleum geologists. Snider [8] expressed the currently accepted views in a later critical comment. Under the circumstances, it is gratifying to learn of the confirmatory evidence of recent observations in the same region.

WALLACE E. PRATT

FRIJOLE, CULBERSON COUNTY, TEXAS,
June 24, 1954

[8] Snider, L. C., 1927, Suggested explanation for surface subsidence in Goose Creek oil field: Bull. Amer. Assoc. Petroleum Geologists, Vol. XI, p. 729.

REVIEWS

Pegmatite Investigations 1942–45 New England. By EUGENE N. CAMERON, DAVID M. LARRABEE, ANDREW H. MCNAIR, JAMES J. PAGE, GLENN W. STEWART and VINCENT E. SHAININ. Pp. viii, 352; pls. 48; figs. 139. U. S. Geological Survey, Professional Paper 255.

This professional paper is one of a monumental series reporting the results of the World War II study of pegmatites by the U. S. Geological Survey. Reports on the pegmatites of Colorado, Wyoming, and Utah (Professional Paper 227); of Idaho and Montana (Professional Paper 229); of the Black Hills (Professional Paper 247); and of the Southeastern Piedmont (Professional Paper 248) have already appeared. Two of the authors of the present report, Cameron and McNair, with R. H. Jahns and L. R. Page, have also presented their very significant analysis of the internal structure of granitic pegmatites in Monograph 2 of this journal.

The pegmatite investigations of World War II, like those of World War I, very naturally had a strong economic emphasis. The emphasis, moreover, was more specifically on those economic phases which might yield results within a relatively short period, such as structural mapping. The present work of 352 pages with 48 plates and 139 text figures includes a summary of the history of pegmatite mining in New England, a discussion of the geologic setting of the pegmatites, a general description of pegmatites with emphasis on structural zoning, and an appraisal of the various economic minerals of pegmatites. The bulk of the report, and its greatest contribution, is devoted to detailed descriptions of the various mines and prospects. More than 300 pegmatites were mapped in this study and in most, lithologic and structural zones were delineated. All maps show topographic contours and some, structural contours as well. The maps are particularly valuable because they show actual outcrops and are fairly large scale—40 to 80 feet to the inch. Most of the maps are of individual deposits, but some are of geologic areas containing a number of pegmatites.

A number of the pegmatites described in this report were also described in U. S. Geol. Survey Bull. 740 (Mica Deposits of the United States) and a comparison of the two reports shows not only a considerable change in the development of the deposits between World Wars I and II but also a great improvement in the detail of the later geologic mapping. The introduction of some diamond drilling and the wide use of the mapping of zones have led to a far better understanding of the size and shape of pegmatites. It is only now that sufficient evidence has been accumulated to determine the size and shape of some of the more productive pegmatites. The Strickland pegmatite of Portland, Connecticut, for example, has been mined intermittently for more than fifty years. The mine map together with diamond drill holes put down by the Federal Bureau of Mines clearly shows the body is lens shaped, 720 feet long, 240 feet measured along the dip and 8 to 60 feet thick. The crest plunges both north and south. The keel where exposed in the Cramer mine is nearly horizontal. The authors found here and in other instances strong support for the previous conclusion of Landes that pegmatites do not extend downward for great distances and that most are lenticular. Essentially concordant pegmatites are more common in schists and discordant bodies in the more massive gneisses.

The authors show convincingly that zonal mapping is very important in ap-

praising the economic possibilities of pegmatites, since the various minerals have characteristic modes of occurrence. In addition to a reappraisal of the mica and feldspar deposits, the report contains the first comprehensive appraisal known to the reviewer of the beryl reserves of New England. As of 1945, the total known beryl in New England was estimated as 1,140 tons indicated and 1,231 tons inferred. The beryl was estimated in most cases by counting beryl crystals on quarry faces and on natural surfaces. In the few cases when such estimates have been checked by analyses of bulk samples, the results have checked remarkably well.

Some of the statements about the ages of the pegmatites are subject to criticism, but it should be said also that the ages of the pegmatites are not of fundamental importance in this report, which is primarily economic. In the present state of our knowledge it seems better to this reviewer to state ages based on lead-uranium ratios in years with only tentative assignment to periods. In recent years Holmes,[1] Knopf,[2] and Rodgers [3] have pointed up some of the problems of matching a time-scale in periods based on geological evidence and one in years based on lead-uranium ratios. The authors, moreover, have apparently accepted the ages based on analyses of radioactive minerals without due regard to the probable errors. They point out, for example, that in the Middletown district the range in calculated ages from several analyses of radioactive minerals is considerable (*27* million years). They suggest that "it is possible that more than one generation of pegmatites is represented even if all the pegmatites were formed in the Late Devonian time." Since only one analysis included isotopic determinations, and only this one could be corrected for common lead, a range in the calculated ages of *27* million years is not meaningful, for according to Holmes [4] the correction for common lead in the age of the Spinnelli samarskite was 40 million years. This is not to deny the possible occurrence of more than one generation of pegmatite within an orogenic epoch but to prove it by this method, more accurate analyses are required than are presently available. A very recent paper by Kulp, Bate, and Broecker [5] gives some hope that an accuracy of 2 percent may be possible in the near future. The geologic evidence cited of one pegmatite cutting another at the Cramer mine shows clearly more than one generation of pegmatite but gives no clue as to age difference.

Probably the more a work contributes in sound basic data and well-conceived generalizations, the more it whets the appetite for even further information and better understanding. The authors clearly recognize some of the directions additional investigations should take. Geochemical studies of pegmatites and possible genetically related igneous rocks are suggested. Detailed areal studies on an adequate scale should yield much knowledge of the structural control of the intrusions and the origin of the pegmatites. The problems of pegmatites are far from solved, but this report and others of the U. S. Geological Survey have added new and fundamental data.

JOE WEBB PEOPLES

WESLEYAN UNIVERSITY,
MIDDLETOWN, CONNECTICUT,
June 28, 1954

[1] Holmes, Arthur, The construction of a geological time-scale: Geol. Soc. of Glasgow Trans., vol. 21, pt. 1, p. 117–152.

[2] Knopf, Adolph, 1949, Time in earth history, p. 1–9: In Genetics, paleontology, and evolution, Princeton Univ. Press.

[3] Rodgers, John, 1952, Absolute ages of radioactive minerals from the Appalachian region: Am. Jour. Sci., p. 411–427.

[4] Op. cit., p. 137.

[5] 1954, Present status of the lead method of age determination: Am. Jour. Sci., vol. 252, p. 345–365.

General Chemistry. By EUGENE G. ROCHOW and M. KENT WILSON. Pp. xiii, 602; figs. 154; tbls. 22. John Wiley & Sons, Inc., New York, 1954. Price, $6.00.

Most geologists lean heavily on chemistry, and those of older or inadequate training in chemistry seek the newer ideas in language that is understandable to them. This book may have such an appeal. It is written for freshmen and is designed to cover portions of the field rather than the whole. It relates chemical fundamentals to present experience. As the authors say in their preface, "We had a particular problem, we were given the unusual privilege of attacking it exactly as we pleased. . . . We have assembled a unified group of chemical principles that we believe will provide a sound fundamental training in chemistry. . . ."

The content is interestingly arranged. The 28 chapters lead the reader through fundamentals to applications. They start off with atoms, and the periodic table and then consider three examples for experience, copper, silver and gold. Next is given an introduction to gases, liquids and solids, with theories and practical applications. Chemical equilibrium and oxidation follow, the latter illustrated by H_2O_2 and the halogen elements. Intervening is a chapter on "The Sea as a Chemical Storehouse." Other chapters deal with sulfur and its congeners, chemistry and electricity, heat of reaction, photochemistry, photosynthesis, biochemistry, chemotherapy, "Cousins of Carbon," macromolecules, radiochemistry, metals in theory and practice, and "Our Resources." Appendices follow on the history of chemistry, mathematical concepts and operations, review of chemical arithmetic, and "Answers to Problems."

The book is well written, but sparsely illustrated. It should serve as a good textbook of elementary chemistry.

Principles of Geomorphology. By WILLIAM D. THORNBURY. Pp. 618; figs. 275. John Wiley & Sons, Inc., New York, 1954. Price, $8.00.

The author of this modern work approaches the subject from a somewhat new aspect, namely, a study of fundamental principles before interpretation of land forms is attempted. He also introduces a chapter on applied geomorphology for appeal to "practical geologists."

Of the 22 chapters, the first three deal with background, fundamental concepts, and analysis of geomorphic processes. The last two are called "tools of the geomorphologist" and "applied geomorphology." The intermediate chapters carry about the same headings as a textbook on physical geology. The contents of these chapters is largely physical geology dealing with weathering, fluvial cycles, stream deposition, peneplains, topography controlled by structures, glaciation, arid cycles, coastal changes, volcanism. Each, however, has a geomorphic slant and each is concluded with a list of references.

The book is well written, nicely printed and includes excellently chosen and illustrative photographs. It will probably win first place among geomorphology textbooks.

The Pacific Northwest. Edited by OTIS W. FREEMAN and HOWARD H. MARTIN. Pp. 540; pls. 24; figs. 58. John Wiley & Sons, Inc., New York, 1954. Price, $8.50.

This second edition is almost entirely rewritten by thirty contributors, thirteen of whom are new authors to this book. The editors, both geographers, have uni-

fied the material to give balance and unity. The intention is to offer a coherent account of the present economics, social, human and physical status of the Northwest. The organization is premised on the idea that a knowledge of the physical characteristics and natural resources is essential to the understanding of the economic pattern and problems of the region. The book deals with human adjustments, physical environment, exploitation and conservation of natural resources (nothing about mineral resources), agriculture, industry, commerce and urban development. As in the earlier edition, there are many good maps, charts and photographs. The book is recommended to those interested in the geography of this Pacific Northwest region of the United States.

Minnesota's Rocks and Waters. By GEORGE M. SCHWARTZ and GEORGE A. THIEL. Pp. 366; figs. 161. University of Minnesota Press, Minneapolis, 1954. Price, $4.00.

This interesting book is more than a mere bulletin of local geology and mineral resources of a state. In it the authors portray, in simple language suitable for the layman, a story of geology. Part I and Part II conduct the reader through a series of geological excursions in different parts of Minnesota. Part I, which is good reading for any amateur, regardless of whether he lives in Minnesota, considers land forms, rivers and lakes, minerals and rocks, geologic time, ancient rocks and paleozoic seas, age of reptiles and ice, and Minnesota's mineral resources.

In Part II observations of geological field trips are blended in with local and broader interpretative geology. Appendices list the minerals and rocks of Minnesota, and an excellent glossary of geologic terms used in the book. This last will be handy for any student of elementary geology.

The book is well written and profusely illustrated, and should serve a worthwhile purpose. Similar books, if as authoritatively written, would be welcome from other states.

Geology and Iron Ore Deposits of the Granite Mountain Area, Iron County, Utah. By J. HOOVER MACKIN. U. S. Geol. Surv. Mineral Investigations, Field Studies Map 14, 1954.

This ungainly monstrosity, which measures 41 × 54 inches and arrived in a tube 45 inches long, has to be spread out on a draughting table in order to study and read it. We are uncertain if such sheets are to replace the old well-known folios, but if so, it is unfortunate. Librarians will be distraught since few cases available are large enough to hold them. And they are very awkward to read. Mostly they are apt to be folded up and stowed away some place where they will be little read or used.

The upper left quarter contains a colored geologic map 18 × 24 inches on a scale of 1:12,000—an excellent scale. The upper right quarter contains the legend and structive sections—when folded in half the legend is separated from the map. The lower left quarter contains text in fine type, and the lower right additional text and some sections.

When one wrestles with the awkwardness, he is mollified to find an excellent map whose scale permits detailed depiction of many faults, some of which bound in part a main elliptical intrusion of quartz monzonite whose joint pattern is indicated in detail. The intrusives have marginal bodies of hematite and magnetite that replace surrounding Homestake limestone. In addition fissure veins of magnetite occur in the quartz monzonite.

The author adduces evidence to show that the mineralizing emanations sprang directly from the quartz monzonite bodies themselves as "mother and daughter" rather than that both emanated from the same deep source as "brother and sister." Tension joints in the cooled portion of the intrusive permitted the upsurge of emanations from the consolidating magma beneath. The iron is considered to have been released by the chemical decay of the dark minerals during the progress of crystallization of the magma.

The ore bodies range up to 1,000 feet long and deep, and 230 feet wide. The iron content ranges from 40 to 60 percent and the shipping grade has averaged 53 percent. Magnetite constitutes from 15 to 60 percent of the iron oxides.

If the reader is willing to overcome his objections to trying to read such an ungainly sheet he will find an excellent piece of large-scale mapping, and an intriguing and interesting text with some unusual conclusions, based upon careful field observations and microscope study. The author is to be congratulated for a fine piece of work.

BOOKS RECEIVED

KURT SERVOS

National Academy of Sciences, National Research Council—Washington, D. C., 1953.

Pub. 306. Symposium on Microseisms. Pp. 125; figs. 79; tbls. 12. *A group of papers and accompanying discussions dealing with microseisms of various origins; theories of microseisms.*

U. S. Atomic Energy Commission—Oak Ridge, Tennessee, 1953.

RME-3089. Studies in Sedimentology of the Shinarump Conglomerate of Northeastern Arizona. E. D. McKee, C. G. Evensen, and W. D. Grundy. Dept. of Geology, Univ. of Arizona, Tucson. Pp. 48; tbls. 10; figs. 6; pls. 7. *Studies of composition, texture, cross-stratification, small primary structures, basal contact, paleogeography, and mineralization controls.*

California Department of Natural Resources—San Francisco 11, 1954.

Vol. 50, No. 2. California Journal of Mines and Geology.

Nineteenth Century Mines and Mineral Spring Resorts of Lake County, California. F. J. Simoons.

Mines and Mineral Resources of Santa Clara County, California. F. F. Davis and C. W. Jennings. Pp. 293–430; pl. 1; figs. 26. *One paper deals with the history of mining and production in Lake County during the last century. In Santa Clara County 67.4% of the mineral production 1850–1950 was nonmetallic, more than 30% mercury. A geologic map of this county, 1:126,720, also shows economic mineral deposits.*

Spec. Rept. 39, Div. of Mines. Barite Deposits near Barstow, San Bernardino County, California. Pp. 8; fig. 1. Price, 50 cts. *Detailed geology of barite veins in four neighboring areas. One geologic map is 1:4800, two are 1:3600, a fourth is 1:360.*

Quarterly of the Colorado School of Mines—Golden, 1954.

Vol. 49, No. 2. An Introduction to the Study of Rock Building Algae and Algal Limestones. J. H. Johnson. Pp. 117; tbls. 10; pls. 62. Price, $2.50. *Systematic approach to the study of algae.*

Vol. 49, No. 3. Potentiometric-Model Study of Edge-Water Encroachment. W. J. MASON. Pp. vi, 30; tbls. 2; figs. 14. Price, $1.00. *Laboratory study relating to production rate in the Tensleep pool of the South Elk Basin Field.*

Georgia Division of Conservation (Geological Survey)—Atlanta, 1953–54.

Circ. No. 1. Publications on the Geology and Mineral Resources of Georgia. Pp. 11. *List of 100 publications from 1891 to 1954. Index map, 1:1,000,000.*

Circ. No. 2. Directory of Georgia Mineral Producers. Pp. 40.

State Geological Survey of Illinois—Urbana, 1954.

Rept. No. 172. Structural History of the Centralia Area. R. L. BROWNFIELD. Pp. 31; pls. 11; tbl. 1. *Study based on subsurface data from well logs of this coal and oil region accompanied by two structure and five isopach maps.*

Rept. No. 173. High Temperature Phases from Kaolinite and Halloysite. H. D. GLASS. Pp. 193–207; tbl. 1; figs. 2. *Differential thermal and x-ray diffraction analyses of some clay minerals. Fluxing impurities control development of phases at high temperatures.*

Circ. No. 188. Short Papers on Geologic Subjects. H. R. SCHWALK, J. S. DOBROVOLNY, AND W. D. JOHNS. Pp. 142–168; figs. 5; tbls. 4. *Three miscellaneous papers dealing with areal geology, commercial sand and gravel, and ceramic clay, respectively.*

Circ. No. 189. Twenty-Five Years of Engineering Geology in Illinois. G. E. EKBLAW. Pp. 7–16.

Circ. No. 190. Plastic and Swelling Properties of Illinois Coals. O. W. REES AND E. D. PIERRON. Pp. 11; pl. 1; figs. 2; tbls. 3. *Includes description of apparatus and definitions.*

State Geological Survey of Kansas—Lawrence, 1954.

Bull. 109, Part 4. Additional Studies of the Cenozoic of Western Kansas. D. F. MERRIAM AND J. C. FRYE. Pp. 12; pls. 2; tbl. 1. *Sub-Cenozoic geology, structure and topography based on subsurface data.*

Part 5. Thickness Maps as Criteria of Regional Structural Movement. WALLACE LEE. Pp. 65–80; figs. 10. *Cursory analysis of isopachous maps in interpreting regional structure.*

Part 6. Graded Slopes in Western Kansas. J. C. FRYE. Pp. 81–96; pls. 2; fig. 1. *Graded surfaces of interfluves developed in pre-Illinoian time are due to lateral planation; post mid-Wisconsin "concavo-convex" gullies were cut by surface sheet action of running water.*

Bureau of Business Research, University of New Mexico—Albuquerque, 1954.

New Mexico Studies in Business and Economics No. 1. Natural Gas in New Mexico. V. T. XIMENES. Pp. 73; tbls. 20; figs. 5. Price, $1.25. *Statistical data of production and economics. Includes useful glossary of terms used in the industry.*

North Dakota Geological Survey Circulars, Nos. 68–77. *Each circular contains lithologic description of rocks encountered in drilling the following wells: Walter Waswick No. 1, A. J. Artz No. 1, Lester Kelstrom No. 1, Thorson Ekrehagen No. 1, Klokstad No. 1, Herman Haugen No. 1, Ellis No. 1, Henry Schmidt No. 1, North Dakota "E" No. 1, Wachter No. 1.*

Division of Geological Survey of Ohio—Columbus, 1954.

Inf. Circ. No. 13. The Geology of Lake Hope State Park. M. F. MARPLE. Pp. 30; figs. 21. Price, 25 cts. *For the layman.*

Petroleum and Natural Gas Series No. 51. Rept. of Investigations No. 20. 1953 Oil and Gas Well Drilling Statistics. R. L. ALKIRE. *Summary of statistics in production and operation for 1953.*

Ohio Department of Natural Resources, Division of Water—Columbus, 1953.

Bull. 26. The Water Resources of Cuyahoga County, Ohio. J. D. WINSLOW, G. W. WHITE, AND E. E. WEBBER. Pp. 123; pls. 60; tbls. 29. *Geography, surface and ground water, rock properties, and chemical quality of water.*

Texas Bureau of Economic Geology—Austin, 1953–54.

Rept. of Investigations No. 18. Stratigraphy and Petrology of the Tascotal Mesa Quadrangle, Texas. R. L. ERICKSON. *Descriptive geology of the quadrangle; geologic map, 1:62,500.*

Rept. of Investigations No. 19. Paleontology of the Rustler Formation, Culberson County, Texas. J. C. WALTER, JR. Pp. 679–702; pls. 4; figs. 3. *Fossils described substantiate the Permian age of the Rustler formation.*

Rept. of Investigations No. 20. Cretaceous of Llano Estacado of Texas. J. P. BRAND. *Some of the rocks are chemically or mechanically suitable for use as building materials.*

Rept. of Investigations No. 23. Phosphorite in Eastern Llano Uplift of Central Texas. V. E. BARNES. Pp. 9; figs. 2. *Deposits are small, low grade and of questionable commercial value.*

Virginia Geological Survey—Charlottesville, 1954.

Reprint Series No. 16. Structural Framework and Mineral Resources of the Virginia Piedmont. W. R. BROWN. Pp. 21; figs. 2; pls. 2. *Structure and stratigraphy; brief description of deposits of gold, pyrite, lead-zinc, copper, iron, titanium, manganese, barite, soapstone, feldspar and mica.*

Carte Géologique de l'Algérie. 2nd Edition. Scale 1:500 000, in 6 sheets (30″ × 34″); colored, legend. M. G. BETIER, editor. Govt. of Algeria, 1954. *A well-edited and well-printed edition; colored sheet of geological reconnaissance of the Algerian Sahara accompanies it on same scale.*

Australia Joint Coal Board—Sydney, 1953.

Sixth Annual Report of the Joint Coal Board for the Financial Year 1952–53. Pp. 112; tbls. 40. *Open-cut mines produced less; underground mines produced more in 1952–53. Mining and production statistics and economic and industrial data are detailed, supplemented by tables.*

Canadian Department of Mines and Technical Surveys—Ottawa, 1954.

Bibliography of Seismology No. 13. Pp. 259–277. Price, 25 cts. *Contains 188 bibliographic entries from foreign and domestic journals.*

Geological Survey, Colony of Fiji—Suva, 1953.

Council Paper No. 5. Annual Report for 1953. *Administrative report including abstracts of various geological reports of areas covered.*

Geologie—Berlin, 1953–54.

Jahr. 2, Nr. 6. Pp. 399–470. *Three papers dealing with paleobotany (Cretaceous), vertebrate paleontology (Pleistocene), sedimentology (Permian) and other miscellany.*

Jahr. 3, Beiheft No. 1. Pp. 96. *Miscellaneous papers and notices.*

Beiheft No. 9. Stratonomische Beobachtungen in den Magerkohlenschichten (Namur ob. C.) Westfalens. K.-H. GRIBNITZ. Pp. 40; figs. 9. *Detailed discussion of cyclothems and noncoking coals of Pennsylvanian age in Westfalia. These and some other European examples are compared with those of our central interior. The origin of cyclical sediments takes up six pages.*

Beiheft No. 10. Allgemeine Küstendynamik und Küstenschutz an der südlichen Ostsee zwischen Trave und Swine. KURD V. BÜLOW. Pp. 87; pls. 5; figs. 34. *The protection of coast lines and coastal marine geology are related to geologic processes of erosion and sedimentation. The discussion is generalized from observations in the southern littoral of the Baltic Sea.*

Geological Survey of Japan—Hisamoto-cho, Kawasaki-shi, Japan, 1953–54.

Rept. No. 157. Report on the Geology of the Eastern Part of Yumoto, Iwaki District, Central Part of Joban Coal Field, Fukushima Prefecture. KANJI SUGAI AND HIROSHI MATSUI. Pp. 63; pls. 2. *Of six seams in the Iwaki formation (Oligocene) only one is economic. Probable reserves are approximately 33.5 million tons. Geologic map, 1:20,000; numerous profiles. Text in Japanese, résumé in English.*

Rept. No. 158. Geology of the Matsuo-Hachimantai Sulphur Deposits District, Iwate Prefecture. YOSHINORI KAWANO AND FUJIO UEMURA. Pp. 14. *Sulphur deposit is in altered andesite lavas and pyroclastics of Pleistocene age. Text in Japanese; résumé in English. Geologic map, 1:20,000.*

Rept. No. 159. Some Examples of Structural Control on the Ore Deposits in Japan. Metal Section. Pp. 28. *Well-illustrated report on ore bodies related to structural features. In Japanese.*

Rept. No. 160. Report on the Investigation of the Ground Water for Fabric Industry of West-Banshu Area, Hyogo Prefecture. NOBUO KURATA. Pp. 18. *The chemical properties of the water are conducive for industrial and public consumption. In Japanese. Ground water map 1:30,000.*

Geological map of the Suwa quadrangle, scale 1: 50,000.

Geological Survey Department of Malaya—Kuala Lumpur, 1953.

Memoir No. 7. The Geology and Mineral Resources of the Neighborhood of Kuala Selangor and Rasa, Selangor, Federation of Malaya, With an Account of the Geology of Batu Arang Coal Field. Pp. xi, 163; tbls. 24; pls. 5; figs. 9. Price, $6.00 (Straits). *Upper Paleozoic and Triassic rocks are intruded by granite of Upper Mesozoic (?) age. Economic deposits include tin, wolfram, coal, gold, nonmetallics, bauxite, ilmenite, zircon, monazite, and iron. Tin production is expected to return to the 1940 output. Probable reserves of coal are 21,000,000 tons. The description of the stratigraphy and structure is comprehensive. Two geologic maps, 1:63,360.*

Somaliland Oil Exploration Company, Limited—Hargeisa, 1954.

A Geological Reconnaissance of the Sedimentary Deposits of the Protectorate of British Somaliland. Pp. vii, 42; pls. 3; figs. 7. Price, 15s. *Detailed account of Mesozoic and Cenozoic stratigraphy and of tectonics (intermittent from post-Late Eocene to recent times). A shatter zone affords the only free seepage oil of the Horn of Africa. Oil seems to be confined to rocks of Jurassic age and seems to be controlled by structure. Geologic map, 1:1,000,000; numerous cross- and columnar sections.*

The Geological Society of South Africa—Hortors Limited, Johannesburg.

Alex. L. du Toit Memorial Lectures No. 3. Gondwanaland and the Distribution of Early Reptiles. S. H. HAUGHTON. Pp. 30; figs. 10; tbls. 2. *Review of stratigraphic and paleontological evidence of Atlantic ocean regions bearing on Gondwanaland.*

Geological Survey of the Anglo-Egyptian Sudan—Khartoum, 1954.

Report for 1952–53. GERALD ANDREW. Pp. 20; index map, 1:250,000. Price, P.T. 25 or 5/–. *Includes short notes on the economic, water-supply and engineering geology, geophysical surveys and drilling.*

Acta Geologica Taiwanica, No. 5—Taipeh, Taiwan, December, 1953.

Taiwanite, a New "Basaltic" Glassy Rock of East Coastal Range, Taiwan, and Its Bearing on Parental Magma-Type. V. C. JUAN, H. TAI, AND F. H. CHANG. Pp. 25; pls. 4; tbls. 17; figs. 2. *Taiwanite is proposed for a rock high in MgO, low in Al_2O_3, with sp. gr. 2.780, $N_{av} = 1.589$, and with euhedral crystals of olivine and labradorite in a glassy matrix.*

SOCIETY OF ECONOMIC GEOLOGISTS

PROGRAM AND ABSTRACTS OF PAPERS TO BE PRESENTED AT THE JOINT MEETING OF THE SOCIETY OF ECONOMIC GEOLOGISTS AND THE GEOLOGICAL SOCIETY OF AMERICA, AT LOS ANGELES, CALIFORNIA, NOVEMBER 1–3, 1954

MONDAY MORNING, GOLDEN STATE ROOM

PHILLIP MERRITT and EDWARD WISSER, *Cochairmen*

(After each paper 5 minutes is allowed for discussion)

1. 9:00 Patrick M. Hurley: *Use of the gamma ray scintillation spectrometer in the separate measurement of the uranium and thorium series in geological materials*
2. 9:15 Roger Y. Anderson * and Edwin B. Kurtz: *Studies of some factors influencing uranium accumulation in plants*
3. 9:30 John A. S. Adams: *Uranium contents of Wisconsin rivers and their use in geochemical prospecting*
4. 9:45 George E. Becraft * and Darrell M. Pinckney: *Uranium deposits of the Boulder batholith, Montana*
5. 10:00 Y. William Isachsen: *Uranium deposits, Big Indian Wash-Lisbon Valley area, San Juan County, Utah*
6. 10:20 Irving J. Witkind: *Localization of uranium minerals in channel sediments at the base of the Shinarump conglomerate, Monument Valley, Arizona*
7. 10:35 A. L. Bush * and H. K. Stager: *Estimation of reserves for uranium-vanadium deposits on the Colorado Plateau*
8. 10:55 Ralph E. Taylor: *Geology and mineralogy of salt and cap rock of the U. S. Gulf Coast salt domes*
9. 11:15 Herbert W. Feely * and J. Laurence Kulp: *Origin of salt-dome sulfur deposits*

MONDAY AFTERNOON, GOLDEN STATE ROOM

W. D. JOHNSTON, JR., and CHARLES PARK, *Cochairmen*

(After each paper 5 minutes is allowed for discussion)

1. 2:00 Donald E. White: *Hydrothermal alteration and other characteristics of five explored hot-spring systems*
2. 2:20 Frank W. Dickson * and George Tunell: *Systems HgS—Na_2S—H_2O and HgS—Na_2S—Na_2O—H_2O*
3. 2:35 S. B. Levin,* W. F. Nye, and H. Kedesdy: *Manganese dioxide for dry cells*

* Indicates speaker.

4. 2:50 H. R. Cornwall * and W. S. White: *Native copper deposits*
5. 3:10 C. B. Sclar * and B. Geier: *Paragenetic relationships of germanite and reniérite from Tsumeb, South West Africa*
6. 3:30 D. L. Graf * and J. E. Lamar: *Significance of carbonate mineralogy in relation to the uses of carbonate rocks*
7. 3:45 F. Beach Leighton: *Origin of vermiculite deposits, Southern Virgin Mountains, Nevada*
8. 4:00 C. W. Wolfe: *Blister hypothesis and economic geology*

BY TITLE

1. Chester K. Wentworth, Arnold C. Mason, and Dan A. Davis: *Salt-water encroachment as induced by sea-level excavation on Anguar Island*

USE OF THE GAMMA RAY SCINTILLATION SPECTROMETER IN THE SEPARATE MEASUREMENT OF THE URANIUM AND THORIUM SERIES IN GEOLOGICAL MATERIALS

PATRICK M. HURLEY

Mass. Inst. of Technology, Cambridge, Mass., U. S. Geological Survey

A survey of the gamma scintillation spectra of the uranium and thorium series in equilibrium was made for the purpose of selecting optimum conditions for a method of direct radiometric analysis that will measure separately the quantity of these two components with moderate precision in materials of geologic interest. A successful method has been found, utilizing the gamma radiation from Pb^{212} in the vicinity of 239 kev for discrimination of the thorium series, in comparison with a band in which the thorium series contribution is low. The circuits are sufficiently stable and the discrimination and counting rates have been adjusted to optimum values so that a comparison can be made between a band 80 kev wide centered at 239 kev and a band 60 kev wide centered at approximately 170 kev. Two channels are employed with absolute calibration of each channel at intervals that are small compared to the time of the major variations in discriminator levels.

The method can be used for materials containing as little as a few parts per million of uranium or thorium: such as, for example, most common rocks. The precision of the method and its relation to the Th/U ratio will be discussed. Samples exceeding 100 grams are used for common rock analyses. Materials containing 0.1% equivalent uranium, such as common zircons, may be analyzed in samples of 100 mg. or less.

STUDIES OF FACTORS INFLUENCING URANIUM ACCUMULATION IN PLANTS

ROGER Y. ANDERSON AND EDWIN B. KURTZ

Department of Botany, University of Arizona, Tucson, Arizona

In an attempt to account for the great variability in the accumulation of mineral salts by plants growing in the field, detailed laboratory studies have been made of the factors that influence accumulation with respect to uranium. Plants were

* Indicates speaker.

grown in the greenhouse by nutrient culture methods and analyzed by the alpha scintillation method. Results indicate that different species vary markedly in their ability to accumulate uranium. By determining the relative ability of each species to accumulate uranium. By determining the relative ability of each species to accumulate uranium under standard conditions it should be possible to correlate between species in the field. Uranium accumulation seems to be a linear function of uranium concentration in the soil medium. Some plants increase their uranium content with age while others decrease their content with age. In two plants the older organs contained the most uranium but in a third plant the younger organs tained the most. Low levels of soil phosphate greatly increased the accumulation of uranium, probably by increasing the availability of uranium in the soil. High levels of phosphate delayed flowering in oats, however high levels of uranium, which would be expected to tie up the phosphate, also delayed flowering. Other factors being studied include soil acidity (pH), transpiration, variation within the species in the ability to accumulate uranium, and mineral nutrition. Refinement of the present field methods of bio-geochemical prospecting should be possible by determining the importance of each factor for each species used.

URANIUM CONTENTS OF WISCONSIN RIVERS AND THEIR USE IN GEOCHEMICAL PROSPECTING

JOHN A. S. ADAMS
The Rice Institute, Houston, Texas

Over 100 samples from 18 stations on Wisconsin rivers, including the Mississippi, have been analyzed fluorimetrically for uranium. Uranium contents from 0.01 to 1.1 parts per billion were found, with an over-all average of 0.45 parts per billion. Experiments indicate an average error of $\pm 6.4\%$ of the amount present.

At different seasons of the year one station on the Mississippi showed unsystematic variations from 0.08 to 0.82 parts per billion and other stations on large rivers showed similar variations. Small northern Wisconsin rivers systematically had their maximum uranium concentrations in winter; it is believed that ground water is responsible for most of the uranium in these streams. Southern Wisconsin rivers systematically showed their maximum uranium concentrations in the spring; it is believed that uranium from phosphate fertilizer is responsible for this springtime peak. Analyses of representative samples of phosphate fertilizer used last spring in Wisconsin showed uranium contents from 22 to 56 parts per million, which would give uranium concentrations of about 8 pounds per square mile of fertilized land. These data and material balances based upon them are very useful in making tentative suggestions for a pattern of geochemical prospecting based upon sampling ground and surface waters.

URANIUM DEPOSITS OF THE BOULDER BATHOLITH, MONTANA

GEORGE E. BECRAFT AND DARRELL M. PINCKNEY
U. S. Geological Survey, Spokane, Washington

Uranium minerals have been found in the Boulder batholith in at least three different structural and mineralogic environments. In several mines in the northern part of the batholith, uranium minerals in persistent shear zones cutting the quartz monzonite of the batholith are spatially associated with minerals containing base and precious metals. In discontinuous silicified zones in the quartz monzonite in the northern part of the batholith and at one location west of Butte, uranium

minerals are associated with chalcedonic quartz containing sparse pyrite and very small amounts of other sulfides. The only known occurrence of uranium minerals in the Cretaceous volcanic rocks into which the Boulder batholith was intruded is at the Red Rock mine about two miles west of Basin, Mont. In this deposit, uranium is associated with thorium and rare earths in an intensely altered and brecciated zone.

Almost all the known occurrences of uranium are in the northern part of the batholith. In Butte, only minor amounts of radioactivity have been detected scattered at random throughout the extensive mine workings, although the production of other metals there far exceeds the production elsewhere in the batholith.

URANIUM DEPOSITS, BIG INDIAN WASH–LISBON VALLEY AREA, SAN JUAN COUNTY, UTAH

Y. WILLIAM ISACHSEN

1001 Ute Avenue, Grand Junction, Colorado

Extensive bedded uranium deposits have been discovered about 32 miles south-southeast of Moab, Utah. These deposits occur in sediments along the southwest limb of the Lisbon Valley salt anticline. The major orebodies are confined to the lower portion of the Triassic Chinle formation which unconformably overlies the Permian Cutler formation. Arkosic, gray to black sandstone with intercalated lenses of gray-green mudstone and mudstone pebble conglomerate contain uraninite which has replaced carbonaceous material and calcite cement. Locally, solid masses of pure uraninite result from replacement of organic material. Montroseite occurs with uraninite in the major deposits discovered to date. Tyuyamunite frequently forms surface coatings along fractures. Thickness of ore in the area is generally sufficient to permit mining with little or no waste rock.

In several areas known to contain orebodies, the gray-green color of the lower Chinle formation extends upwards into the overlying red Chinle mudstones in the manner of an alteration halo. About 100 feet beneath the Chinle ore horizon are arkosic lenses in the Cutler formation which contain, in some instances, low grade uranium mineralization. The ore minerals, carnotite and becquerelite, are disseminated in the arkose with greatest concentration adjacent to fractures. The oxidized state of these minerals coupled with the concentration near fractures suggests that the Cutler mineralization is due to leaching from uraninite orebodies in the Chinle formation.

LOCALIZATION OF URANIUM MINERALS IN CHANNEL SEDIMENTS AT THE BASE OF THE SHINARUMP CONGLOMERATE, MONUMENT VALLEY, ARIZONA

IRVING J. WITKIND

U. S. Geological Survey, Denver Federal Center, Denver, Colorado

During the summers of 1951 and 1952 the U. S. Geological Survey mapped the geology and uranium deposits in three 15-minute quadrangles on the Navajo Indian Reservation in Apache and Navajo counties, northeastern Arizona. Ages of exposed sedimentary rocks range from Permian, represented by the Halgaito tongue of the Cutler formation, to Jurassic, represented by the Salt Wash member of the Morrison formation. The dominant structural element of the area is the Monument upwarp, a large asymmetrical anticline whose northern end is near the

junction of the Green and Colorado Rivers in Utah and whose southern end is near Kayenta, Arizona. North-trending subsidiary asymmetrical anticlines are superimposed on the upwarp.

Uranium ore bodies are localized in the conglomeratic sandstone of the Shinarump conglomerate (Triassic) that fills channels scoured in the underlying Moenkopi formation (Triassic). These channels range in cross section from 15 feet wide and 10 feet deep to 2,300 feet wide and 70 feet deep. Fragments of trees were deposited with Shinarump sediments in the channels. It is suggested that when the Shinarump conglomerate was invaded by mineralizing solutions they deposited the uranium ore mainly in places where decomposing plant material had been. It is also suggested that short channels are more likely to contain ore than long channels.

THE ESTIMATION OF RESERVES FOR URANIUM–VANADIUM DEPOSITS ON THE COLORADO PLATEAU

A. L. BUSH AND H. K. STAGER

U. S. Geological Survey, Grand Junction, Colorado

Because of their variance in grade, size, and shape, carnotite deposits of the Colorado Plateau present special problems when estimating reserves. To obtain comparable results from various appraisers, the U. S. Geological Survey has adopted basic assumptions and standardized rules for calculating reserves.

Deposits are generally considered as tabular masses. Projections between and beyond sample points are governed by geologic reasoning. A bi-metal grade scale is used because of the intimate association of uranium and vanadium and the marketability of both minerals. Mineralized material that does not meet strict cutoffs in both grade and thickness is excluded from the reserves.

To determine the accuracy of the original reserve estimates and their significance in terms of total reserves, a reappraisal was made of 30 representative deposits after they had been developed by mining. Original estimates for some individual deposits were far too high, in both tonnage and grade, and others were much too low. For the total of deposits reappraised, however, the original estimates were only slightly low in tonnage and V_2O_5 grade and the U_3O_8 grade had been estimated accurately.

GEOLOGY AND MINERALOGY OF SALT AND CAP ROCK OF U. S. GULF COAST SALT DOMES

RALPH E. TAYLOR

Humble Oil & Refining Company, Houston, Texas

Active development of oil, salt, and sulphur resources during the last 15 years has greatly increased knowledge about salt domes. The 235 domes proved by drilling and many additional "geophysical prospects" occur in closely related Gulf Coast basins extending from Alabama to Mexico.

Typically, the salt of domes is a compact aggregate of halite grains associated with varying amounts of disseminated sand-size anhydrite grains concentrated in complexly folded bands. Sedimentary origin of the salt is known from its chemical and mineral composition, banding or bedding, and inclusions of gas, liquid, and fragments of anhydrite, sand, and shale beds. Anhydrite and some 20 other minerals associated with halite were formed by precipitation from sea water during

halite deposition. Deep wells at margins of basins have cored horizontally bedded salt that has been called Jurassic; dome salt is different mineralogically and is probably older.

Additional evidence that cap rock is residue accumulated after solution of dome salt has been provided by discovery that at most domes the salt contains large quantities of anhydrite grains. Distinctive inclusions of bedded anhydrite found recently in both salt and cap rock cores from the same domes also indicate residual origin.

It is concluded that the new data substantiate the theories of intrusive origin of salt domes from deposits of bedded salt and residual origin of cap rock from solution of this salt. Salt is mined at a number of domes and cap rock is important in production of oil and sulphur at several.

THE ORIGIN OF SALT-DOME SULFUR DEPOSITS

HERBERT W. FEELY AND J. LAURENCE KULP

Lamont Geological Observatory (Columbia University), Palisades, New York

The application of isotopic techniques, laboratory reactions, and bacteriological studies has produced new information on the origin of the Gulf Coast salt dome sulfur deposits. Laboratory experiments designed to produce hydrogen sulfide or sulfur through the direct reduction of anhydrite by petroleum gave negative results in time equivalents of millions of years. On the other hand sulfate-reducing bacteria have been employed to produce native sulfur from dissolved sulfate. Under conditions within the range of those found in salt domes bacterial reduction caused sulfur isotopic fractionation of 1.4%. This is the same order of fractionation as that observed between anhydrite and sulfur from the Newgulf Salt Dome.

These data, together with reported similarities in C^{12}/C^{13} ratios in the petroleum and in the limestone cap rock from the domes, strongly favor the theory that the reduction of anhydrite takes place by bacterial action in which hydrocarbons serve as an energy source and hydrogen sulfide is the product. The resulting sulfide is oxidized to sulfur, probably by slow reaction with the sulfate. Therefore, conditions favorable for the existence of sulfate-reducing bacteria in the anhydrite cap rock and a long average life of H_2S in the salt dome cap are both essential for the development of a commercial sulfur deposit.

HYDROTHERMAL ALTERATION AND OTHER CHARACTERISTICS OF FIVE EXPLORED HOT-SPRING SYSTEMS

DONALD E. WHITE

U. S. Geological Survey, Menlo Park, Calif.

Hydrothermal alteration of five explored hot spring systems has been studied. Four systems—the Upper Basin and Norris Basin of Yellowstone Park; Steamboat Springs, Nevada; and Wairakei, New Zealand—are relatively high in temperature near the surface and at depth and are of the volcanic type.

Superficial acid leaching occurs in three of the four areas. Deep alteration minerals include adularia, illite, montmorillonite, pyrite, chlorite, calcite, zeolites, kaolinite, and sodic feldspar. All have been found at Steamboat Springs, most were described from the Upper Basin and Wairakei, but only a few occur at Norris Basin. Fresh rock may occur near the surface but is less common at depth.

Chalcedony, quartz, and calcite are typical vein minerals; opal is dominant near the surface but does not occur below 100 feet. Cinnabar and stibnite occur

at Steamboat, and orpiment and realgar in Norris Basin, but all seem to be restricted to shallow depths. Sinter at Steamboat and Wairakei contains gold and silver.

In some respects the four high-temperature spring systems are similar to epithermal gold-silver deposits.

The fifth system—Sulphur Bank, California—is the only one that has been mined extensively for its metal content (quicksilver). Rock alteration and present temperatures differ notably from those of the other systems. Most alteration is of the superficial acid type; but minor replacement calcite, pyrite, and argillic minerals occur in deeper workings. Cinnabar and opal persist to depths of at least 260 feet. A volcanic source for the ores and thermal waters is not yet certain.

THE SYSTEMS $HgS—Na_2S—H_2O$ AND $HgS—Na_2S—Na_2O—H_2O$

FRANK W. DICKSON AND GEORGE TUNELL

Department of Geology, University of California, Los Angeles 24, Calif.

Field evidence suggests that cinnabar and metacinnabar are deposited from sulfide solutions at temperatures ranging upwards from 100° C and at pressures of a few atmospheres. Since these conditions are attainable in the laboratory the authors have investigated the ternary system $HgS—Na_2S—H_2O$ and the quaternary system $HgS—Na_2S—Na_2O—H_2O$. The saturation curves of cinnabar and metacinnabar in the ternary system $HgS—Na_2S—H_2O$, in the concentration range from 75% to 100% water, have been determined at 25° C, 50° C, and 75° C. The saturation surface of cinnabar in the quaternary system $HgS—Na_2S—Na_2O—H_2O$ in the concentration range from 75% to 100% water has been determined at 25° C. Work now in progress includes determining saturation surfaces in the quaternary system at higher temperatures and a study of the quinary system $HgS—Na_2S—Na_2O—SiO_2—H_2O$.

Saturated solutions were analyzed for mercury, sulfur, and sodium; water percentages were obtained by difference. Solid phases were identified by means of the x-ray spectrometer and petrographic microscope.

MANGANESE DIOXIDE FOR DRY CELLS

S. B. LEVIN, W. F. NYE AND H. KEDESDY

Signal Corps Engineering Laboratories, Fort Monmouth, New Jersey

In the use of manganese dioxide for military dry cells the conflicting requirements of reactivity and stability place critical emphasis on crystallographic features. Within the relatively narrow compositional range permissible, the optimum combination of properties is closely related to phase-type of MnO_2 as revealed by x-ray diffraction, and to crystallinity as revealed by the micro-morphology and the character of the diffraction pattern. The well-crystallized phases are insufficiently reactive; the almost-amorphous phase-types are insufficiently stable in the presence of a fluid medium (the electrolyte) which facilitates ion transport. In polyphase manganese dioxide a minor phase, well crystallized and with acicular morphology, may adversely affect the stability of a major mesocrystalline phase by promoting recrystallization. In spite of difficulties of nomenclature, the distinction of phase types in terms of their crystallographic features is feasible and important. Examples of the important phase types will be illustrated.

NATIVE COPPER DEPOSITS

H. R. CORNWALL AND W. S. WHITE

U. S. Geological Survey, Washington 25, D. C.

Native copper occurs in mafic lavas, hypabyssal diabasic intrusives, ultramafic intrusives, clastic sedimentary rocks, and the oxidized zone of sulfide deposits. Native copper predominates over sulfide copper in mafic lava flows—best exemplified in the Lake Superior region—and in some sedimentary rocks, but is typically subordinate to sulfide copper elsewhere.

Possible origins of native copper include: precipitation from sulfide-bearing hydrothermal solutions in rocks containing ferric oxide; deposition from sulfur-deficient hydrothermal solutions; deposition from meteoric or hydrothermal chloride solutions in the presence of calcite, prehnite, or zeolites; precipitation from hydrothermal solutions by ferrous salts; organic precipitation from meteoric waters; reduction of copper sulfides by meteoric waters in the zone of oxidation; reduction of primary copper sulfides by later hydrothermal solutions.

Traces of native copper in mafic lava are believed to have crystallized as the lava cooled. The native state of the copper is attributed to escape of sulfur in gases during extrusion. Later concentration of this native copper by hydrothermal solutions may form economic deposits. The hot water that formed the Lake Superior deposits need not have been magmatic in origin, but may well have been water buried with the lava and driven up the dip of the flows by heat and pressure in the depths of the Lake Superior basin. More highly metamorphosed lavas with native copper, like the Catoctin greenstone of the Appalachians, the Triassic lavas of Oregon, and lava of Copper River, Alaska, presumably resemble rocks down the dip from the Michigan copper deposits.

PARAGENETIC RELATIONSHIPS OF GERMANITE AND RENIÉRITE FROM TSUMEB, SOUTH WEST AFRICA

C. B. SCLAR AND B. GEIER

Battelle Memorial Institute, Columbus, Ohio; and Tsumeb Corporation, Ltd., Tsumeb, South West Africa

Germanium occurs as germanite and reniérite in the hypogene copper-lead-zinc orebody at Tsumeb, South West Africa. The principal hypogene sulfides that constitute the germanium-bearing ore are galena, tennantite, enargite, digenite, bornite, chalcopyrite, sphalerite, and pyrite. Germanite occurs as minute grains and fine-grained aggregates which are disseminated dominantly through massive granular aggregates of galena, tennantite, and sphalerite and subordinately through the host rock of dolomite. Reniérite occurs as (1) continuous and discontinuous shells of variable thickness around germanite grains and as intergranular networks in aggregates of germanite grains, (2) shells of variable thickness around inclusions of an unidentified mineral in germanite, (3) irregular patches within germanite grains, (4) lamellae of variable thickness developed along the cubic or octahedral planes of germanite so as to form a regular intergrowth with that mineral, and (5) irregular grains disseminated through the host rock of dolomite.

Germanite was one of the earliest minerals formed in the sequence of hypogene sulfide deposition, and reniérite was introduced later principally by replacement of the germanite and subordinately by replacement of the host rock. Replacement of germanite by an equal volume of reniérite requires an addition of iron and the corresponding removal of an approximately equivalent amount of germanium. The intimate association of early germanite and relatively late reniérite provides an example of the mineralogical redistribution of germanium induced by changing hypogene conditions.

THE SIGNIFICANCE OF CARBONATE MINERALOGY IN RELATION TO THE USES OF CARBONATE ROCKS *

D. L. GRAF AND J. E. LAMAR

Illinois State Geological Survey, Urbana, Illinois

The large-scale industrial consumption of carbonate rocks for a wide variety of uses, together with the scientific interest evoked by the natural occurrence of such rocks in most geological environments, promises to stimulate a continuing study of the fundamental properties of the principal rock-forming carbonate minerals.

Many industrially significant properties of carbonate rocks may be explained in terms of crystal structure. Anisotropism of thermal expansion and light transmission are directly related to the oxygen arrangement. Solubility and hardness anisotropy correlate with crystal structure in a more complex fashion. The ordered arrangement of Ca^{++} and Mg^{++} in dolomite requires an activation energy for disruption such that dolomite calcination, without the formation of large, unreactive MgO particles, has been a major problem. The exsolution of unstable Fe^{++} substituted for Mg^{++} in dolomite is one cause of the staining of building stones.

Ionic configuration and charge distribution at carbonate surfaces is involved in studies of the flowability of carbonate powders, the flotation concentration of carbonate minerals, and the reputed reduction of carbonate hardness during drilling through the use of surface-active agents.

Consideration of recent successful research programs on magnesite and dolomite calcination indicates that a broad attack involving knowledge of kinetics, of thermodynamics, and of crystal structures and their mechanisms of transition was necessary. A satisfactory explanation of carbonate crystal strength promises to involve imperfection theory, as well. The shortage of reliable experimental constants for carbonate minerals other than calcite is a considerable hindrance to further progress.

ORIGIN OF VERMICULITE DEPOSITS, SOUTHERN VIRGIN MOUNTAINS, NEVADA

F. BEACH LEIGHTON

Whittier College, Whittier, California

Vermiculite deposits lie within a one mile square area in the Gold Butte mining district, Southern Virgin Mountains, Nevada. They occur in ultramafic sheets and lenses of probable Precambrian age. Peridotites and perknites have intruded Precambrian magmatites, granulites, and quartzites, and now crop out in the interior of an elliptical dome. Vermiculite is widely distributed in the ultramafic rocks, occurring in veins, stringers, pockets, and as scattered flakes.

All vermiculites present must be considered varieties of hydrobiotite, because K_2O is present in every case and represents a contamination by biotite layers. The fact that all samples showed either biotite interleaved with vermiculite, or non-expandable biotite along with hydrobiotite is one of the best evidences that all vermiculite has altered from biotite, which in most cases, is an intermediate product in the alteration of other ultramafic minerals.

Vermiculitization of biotite was largely accomplished by hydrothermal solutions associated with the injection of abundant granitic pegmatites. However, it is believed that meteoric solutions continued the process of vermiculitization after hydrothermal activity ceased, and perhaps, in some cases initiated it.

* Published by permission of the Chief, Illinois State Geological Survey.

BLISTER HYPOTHESIS AND ECONOMIC GEOLOGY

O. W. WOLFE

725 Commonwealth Ave., Boston 15, Mass.

The origins and peculiarities of hydrothermal solutions are readily explained by differential solution or by complete anatexis of previously existing rock under the thermal influence of a Blister area. The unique character of the rocks which are subjected to partial or complete magmatization determines the nature of the hydrothermal solutions which are generated by Blister heat.

Throughout geological time several processes have served to separate the ore metals into distinct spacial positions. If we presuppose an early magmatic earth, magmatic differentiation took place with the forming of the first crust and has reoccurred in every magmatic phase since that time. Weathering, in itself, is a profound agent of separation, witness iron, gold, and other deposits. Sedimentary transfer again results in variation of mineral and metallic concentration, as is well known. Sedimentation produces a similar effect, the mechanical aspects of which are well understood. More is to be learned concerning chemical precipitation and sedimentation, but we are already well aware of the concentration of uranium, manganese, lead and zinc, and other metals in particular sedimentary environments.

If any one of these unique concentrations is then affected by Blister heat, partial or complete metamorphism or magmatization will take place; unique hydrothermal solutions will form; and distinctive metallogenetic provinces will result. It would seem, then, that a proper study of ore deposits begins, not with magmas and the solutions derived therefrom but with the nature of the rocks from which the magmas and the hydrothermal solutions were derived.

SALT-WATER ENCROACHMENT AS INDUCED BY SEA-LEVEL EXCAVATION ON ANGUAR ISLAND

CHESTER K. WENTWORTH, ARNOLD C. MASON, AND DAN A. DAVIS

U. S. Geological Survey, Volcano Observatory, Hawaii National Park, Hawaii; University of Illinois, Urbana, Illinois; and U. S. Geological Survey, Honolulu, T. H.

Anguar, southwesternmost of the Palau Islands, 800 miles southwest of Guam, has an area of 3.2 square miles and consists of reef limestone of Pleistocene and Recent age. In the northwestern part of the island a basin is formed by a ringlike ridge that has a maximum altitude of 150 feet. To the east and south a series of aro-shaped lower ridges and intervening depressions are concentric with the ridge. Beyond these, a low plain with shallow swales comprises the remaining two-thirds of the island. The ridges are composed of indurated limestone, whereas the plain is underlain chiefly by unconsolidated coralline fragments.

Phosphate has been mined from the three types of topographic depressions since 1908. When power equipment was introduced, excavations were extended below sea level. Lakes formed in these excavations and, despite an annual rainfall of 110 inches, contamination of fresh-water supplies and of agricultural land by salt water resulted from tidal pulsations through the fissured rock. Stoppage of mining was imminent unless remedial measures could be devised.

Anguar provides a model of the operations of a Ghyben-Herzberg fresh-water lens on an oceanic island. At numerous lakes, wells, and test holes, continuing observations were made on water levels; amplitude and lag of tidal fluctuations; and mineral content, pH, and temperature of the lens. These observations guided the selection of constantly adjusted remedial measures, which included partitioning of lakes, and bottom filling or back filling of compartments that failed to freshen because of connecting fissures.

SCIENTIFIC NOTES AND NEWS

The SOCIÉTÉ DE L'INDUSTRIE MINÉRALE will celebrate its centenary by a congress of French and foreign specialists in the mining and metal industries, to take place in Paris from June 20th to July 3rd, 1955. While the congress will occupy itself mainly with mining matters, one of the principal Divisions is concerned with the problems of mineral discovery, prospecting and exploration in their widest aspects. The Chairman of the Mineral Discovery Committee is Monsieur F. Blondel, 12 rue de Bourgogne, Paris 7e.

JOHN P. BULWALDA, Professor of Geology, at the California Institute of Technology and authority on structural and engineering geology, died suddenly August 19 on a geological field trip in Frazier Mountain Park, Ventura County, at the age of 67. He had just completed a day of field work with his 21 year old son, Robert, when he died.

LLOYD M. SCOFIELD, mining geologist, announces the opening of a consulting office at 1014 Fidelity Building, 14 West Superior St., Duluth 2, Minnesota.

D. R. DERRY, formerly Chief Geologist for Ventures Limited, left this position on September 1st to join Rio Canadian Exploration Limited, the Canadian subsidiary of the British Company of Rio Tinto Mines Limited, as Executive Vice-President.

THE INDUSTRIAL MINERALS DIVISION OF THE AIME held its annual Fall Meeting at Lake Placid, N. Y., on October 5–9. The papers presented were: (1) "Geology of the Adirondacks," Matt S. Walton, Jr.; (2) "Mineral Economics of Upstate New York," John A. Graham; (3) "Geological Control of Adirondack Mineral Deposits," A. E. J. Engle; (4) "Anorthosite as an Industrial Mineral," J. G. Broughton; (5) "Operations of International Talc Co.," F. G. Keihle and Roger Miller; (6) "Magnetic Anomalies and Geophysical Prospecting in the Adirondacks," LeRoy Scharon; (7) "Wollastonite and Diopside, New Industrial Minerals," Raymond Ladoo; (8) "Commercial Colored Slates of New York and Vermont," D. M. Larrabee; (9) "Geochemistry and Importance of Saratoga Mineral Waters," Lester W. Strock; (10) "Quality Control in the Manufacture of Extender Pigments," Charles H. Pratt; (11) "Industrial Minerals of the Ottawa Valley," N. B. Davis; (12) "Gypsum Deposits at Dutch Settlement, N. S.," C. Olivier Campbell. In addition there were plant visits, field trips, and numerous social events. Invitations to participate in the Fall Meeting as guests were extended to the Mining Society of Nova Scotia, the Industrial Minerals Division of the Canadian Institute of Mining and Metallurgy, and the Society of Economic Geologists.

J. M. RAYNER, Deputy Director of the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development, was appointed Principal Delegate for Australia at the 10th General Assembly of the International Union of Geodesy and Geophysics in Rome, during September, 1954.

HARRISON BROWN, professor of geochemistry at the California Institute of Technology, left Pasadena for a six-month trip to Rome to participate in the

meeting of the International Geophysical Union and present a paper there on recent developments in the determination of geologic time, then to visit geochemical laboratories in Switzerland, France, Belgium and England, and then to India where he will make a study of Indian resources. This survey, which will primarily concern mineral resources, is sponsored by the Rockefeller Foundation and will be carried out with the cooperation of the Indian government. The survey, including visits to Bombay, Calcutta, Madras and Hyderabad, will require approximately three months time.

A BUREAU OF MINES SURVEY TEAM appointed by Secretary McKay submitted a report, released August 3, carrying 39 detailed recommendations, summarized as follows: (1) that the number of regions be reduced from 9 to 4; (2) that administration of health, safety and coal mine inspection activities be separate and apart from scientific and technical research activities; (3) that there be a coordinated strengthening of all statistical and commodity analysis work; (4) that a plan of organization be adopted under which the Washington office retains responsibility for policy and program determination, while conduct and management of research are decentralized. The survey team consisted of: Dr. Curtis L. Wilson, dean of the Missouri School of Mines, Rolla, Mo., chairman; John C. Kinnear, Sr., former vice president, Kennecott Copper Corp., New York; Dennis L. McElroy, vice president, Pittsburgh Consolidation Coal Co., Pittsburgh, Pa.; J. R. Butler, president, Butler Johnson Corporation, Houston, Texas, and member of the petroleum consulting firm of Butler, Miller and Lentz; and vice president of Independent Petroleum Association of America; and Spencer S. Shannon, Bedford, Pa., former director, materials office of the former National Security Resources Board.

ARTHUR R. KINKEL, JR., U. S. Geological Survey, has begun a two-year study of the copper deposits of the Philippine Islands. The project is part of the Foreign Operations Administration's study of the strategic minerals of the Philippines. Mr. Kinkel's address is USAOM-FOA, APO 928, c/o Postmaster, San Francisco, California.

BENO GUTENBERG, professor of geophysics and director of the Caltech Seismological Laboratory; HUGO BENIOFF, professor of seismology; and HARRISON BROWN, professor of geochemistry, are representatives of earth science from the California Institute of Technology at the meeting of the International Geophysical Union held in Rome, September 14–25.

WILLIAM O. HOTCHKISS, former president of the Society of Economic Geologists, died on June 20, 1954.

JOHN W. GABELMAN recently resigned as geologist with the American Smelting and Refining Company in Salt Lake City to accept a position as District Geologist with the Atomic Energy Commission in Grand Junction, Colorado.

W. B. MATHER, Chairman of the Mineral Technology Department, Southwest Research Institute of San Antonio, has returned to the United States after spending four months studying phosphate deposits in Brazil.

THE GEOLOGICAL SOCIETY OF AUSTRALIA publishes a news bulletin of which Vol. 2, No. 1, is now out. There are three issues a year that cover short notes on geological discoveries, and developments, along with reports from state correspondents on geological affairs of Australasia.

THE AAAS ANNUAL MEETING FOR 1954 will be held in Berkeley, California, December 26–31. Section E, Geology and Geography will present a program of

General Geography Session; Earth Sciences from the Air; Smoker and Vice-Presidential Address by Dr. M. F. Burrill; and a General Geology Session. Contributive papers for the sessions on general geography and general geology are invited.

WAYNE MCKENZIE is now field geologist for the American Metal Co., assigned to New Brunswick, Canada.

THE XXTH INTERNATIONAL GEOLOGICAL CONGRESS to be held in Mexico in 1956 announces the following officers and committees: President, Gilberto Loyo, Secretary of National Economy; Vice-Presidents, Luis Padilla Nervo, Secretary of Foreign Affairs; José Angel Ceniceros, Secretary of National Education; Antonio J. Bermúdez, Director General of Petroleos Mexicanos; and Nabor Carrillo Flores, Rector of the University of Mexico. The Executive Committee is: President Jorge L. Cumming, Exploration Manager, Petróleos Mexicanos; Vice-Presidents Manuel Sandoval Vallarta, Under-Secretary of National Education, Director of the National Institute of Scientific Research; Ricardo Monges López, Director of the National Institute of Geophysics; Teodoro Flores, Director of the National Institute of Geology; Gonzalo Robles, Head of the Department of Industrial Research, Bank of Mexico; Raúl de la Peña, Director of the National Research Institute for Mineral Resources; Alfonso de la O Carreño, Head of the Department of Geology, Ministry of Hydraulic Resources; David Segura y Gama, Head of the Department of Mines and Petroleum, Ministry of National Economy; Manuel Alvarez, Jr., Vice-President of the National Institute of Scientific Research; General Secretaries Eduardo J. Guzmán, Chief Geologist, Petróleos Mexicanos; Jenaro González Reyna, Chief Geologist, National Research Institute for Mineral Resources; Treasurer Antonio García Rojas, Exploration Assistant Manager, Petróleos Mexicanos. The official address is: II Congreso Geologico International, Comité Ejecutive Organizador, Balderas 36–302 A, Mexico 1, D. F., Mexico.

THE GEOLOGICAL SOCIETY OF AMERICA published in the June, 1954, issue of its Bulletin: "Bibliography and Index of Literature on Uranium and Thorium and Radioactive Occurrences in the United States. Part 3: Colorado and Utah," by Margaret Cooper of the Division of Raw Materials, U. S. Atomic Energy Commission. Since this 124-page bibliography may prove helpful to both geologists and laymen interested in uranium prospecting, the Society has prepared reprints for public sale at 50 cents per copy. Apply to The Geological Society of America, 419 West 117 Street, New York 27, N. Y.

FRANK C. FOLEY is newly appointed State Geologist and Director of the State Geological Survey of Kansas, beginning August 1, 1954. Dr. Foley formerly was State Geologist of North Dakota and geologist on the U. S. Geological Survey; currently he is head of the Division of Groundwater and Geophysics of the Illinois Geological Survey.

HORACIO J. HARRINGTON, who has been designated as Visiting Research Professor of Geology at the University of Kansas, is working during the summer as paleontologist for the Kansas Geological Survey. Dr. Harrington is former Chief Geologist of the Geological Survey of Argentina and from 1947 to 1954 was head of the Department of Geology at the University of Buenos Aires.

RAYMOND C. MOORE is resigning as State Geologist of Kansas coincident with Dr. Foley's arrival on August 1, 1954. This is a position that he has held for 38

years (since 1916), a longer tenure than almost any other American State Geologist. He is named as Principal Geologist of the Kansas Geological Survey.

JULES DU BAR was assistant instructor in charge of courses in general and stratigraphic paleontology at the University of Kansas in 1953–54. He returned to his place on the faculty of Southern Illinois University in September.

OSWALD C. FARQUHAR, from Oxford University, who has taught during the last 5 years at the University of Aberdeen (Scotland), was appointed as Assistant Professor of Geology at the University of Kansas beginning in February, 1954. He is teaching mineralogy and petrology.

JOHN C. FRYE resigned as Professor of Geology at Kansas July 1, 1954, in order to take up duties as Chief of the Illinois Geological Survey. As a teacher he was active mainly in courses concerned with Pleistocene and ground-water geology.

DONALD E. HATTIN, who was assistant instructor in charge of courses in micropaleontology and historical geology at Kansas in 1953–54, left the Department to begin work as Assistant Professor of Geology at Indiana University in September.

RALPH H. KING will begin work as Research Associate in Invertebrate Paleontology at the University of Kansas in September, 1954, organizing and studying fossil collections both of the Department of Geology and the State Geological Survey.

M. L. THOMPSON, who was Assistant Professor and Associate Professor at the University of Kansas from 1942 to 1946, has resigned from the University of Wisconsin to become Professor of Geology and Chairman of the Department of Geology at Kansas in September, 1954. During the summer he worked for the Kansas Geological Survey.

WALTER L. YOUNGQUIST, now working as geologist for the International Petroleum Company at Talara, Peru, has been appointed Professor of Geology at the University of Kansas starting in the school year 1954–55. Formerly he was on the faculty of the University of Idaho.

The first meeting of the SOUTHWESTERN SECTION OF THE FRIENDS OF THE PRECAMBRIAN was held in Socorro, New Mexico, on June 17–18. Dr. Eugene Callaghan of the host organization, the New Mexico Bureau of Mines and Mineral Resources, presided. The object of the conference was to discuss problems of Precambrian rocks in the southwestern United States; the following topics were considered: (1) distribution of rock types in the Precambrian terranes, (2) distribution and significance of major elements of Precambrian structure and the influence of Precambrian structures on subsequent geologic history, (3) distribution of existing data on Precambrian rocks and problems of correlating these data, and (4) a summary of absolute age determinations that are available for Precambrian rocks of the Southwest. Some 33 geologists were present.

FRANK WHITING, of the geological staff of the St. Joseph Lead Co., has been transferred from the Missouri Lead Belt to Argentina, where he will take charge of geological work at the company's Aguilar property.

DUNCAN R. DERRY, for many years chief geologist with Ventures Ltd., has joined Rio Canadian Exploration Ltd. as executive vice-president. This company is a subsidiary of Rio Tinto Co. Ltd. Its president is Oscar Weiss, geophysicist, of Johannesburg and its vice-president and manager is E. B. Gillanders, well known Canadian geologist.